TR – 185

Estimation of Recharge to the Middle Trinity Aquifer of Central Texas Using Water-Level Fluctuations

Marshall Jennings
Chad Thomas
John Burch
Brian Creutzburg, and
Lance Lambert

TEXAS WATER RESOURCES INSTITUTE

TEXAS A&M UNIVERSITY
OCTOBER 2001

Estimation of Recharge to the Middle Trinity Aquifer of Central Texas Using Water-Level Fluctuations

Marshall Jennings
Chad Thomas
John Burch
Brian Creutzburg, and
Lance Lambert

Edwards Aquifer Research & Data Center
Southwest Texas State University
San Marcos, Texas 78666-4616

March 1, 1999 – February 28, 2001
Grant Number HQ-96-GR-02700

The research on which this report is based was financed by the U.S. Department of the Interior, the U.S. Geological Survey, and the Texas Water Development Board.

Technical Report No. 185
Texas Water Resources Institute
The Texas A&M University System
College Station, TX 77843-2118

October 2001

Table of Contents

List of Figures

List of Tables

Estimation of Recharge to the Middle Trinity Aquifer of Central Texas Using Water-Level Fluctuations

Abstract

A 23-site monitoring well network located in the Trinity Aquifer region of Central Texas, with all wells penetrating the Middle Trinity Aquifer, was used with available values of aquifer storativity and specific yield to estimate recharge to the aquifer for 1999 and 2000. As part of the investigation, the Edwards Aquifer Research & Data Center (EARDC) staff worked with the Texas Water Development Board (TWDB) and local groundwater conservation districts to install five new recording well monitors in the study area, comprising about 4500 square miles. The results of the investigation yielded a method of recharge calculation different from the stream baseflow method now in use. The recharge values obtained by this study were somewhat less than representative results obtained by the stream baseflow method, perhaps due to inadequately defined aquifer storativity and low precipitation throughout much of 1999 and 2000.

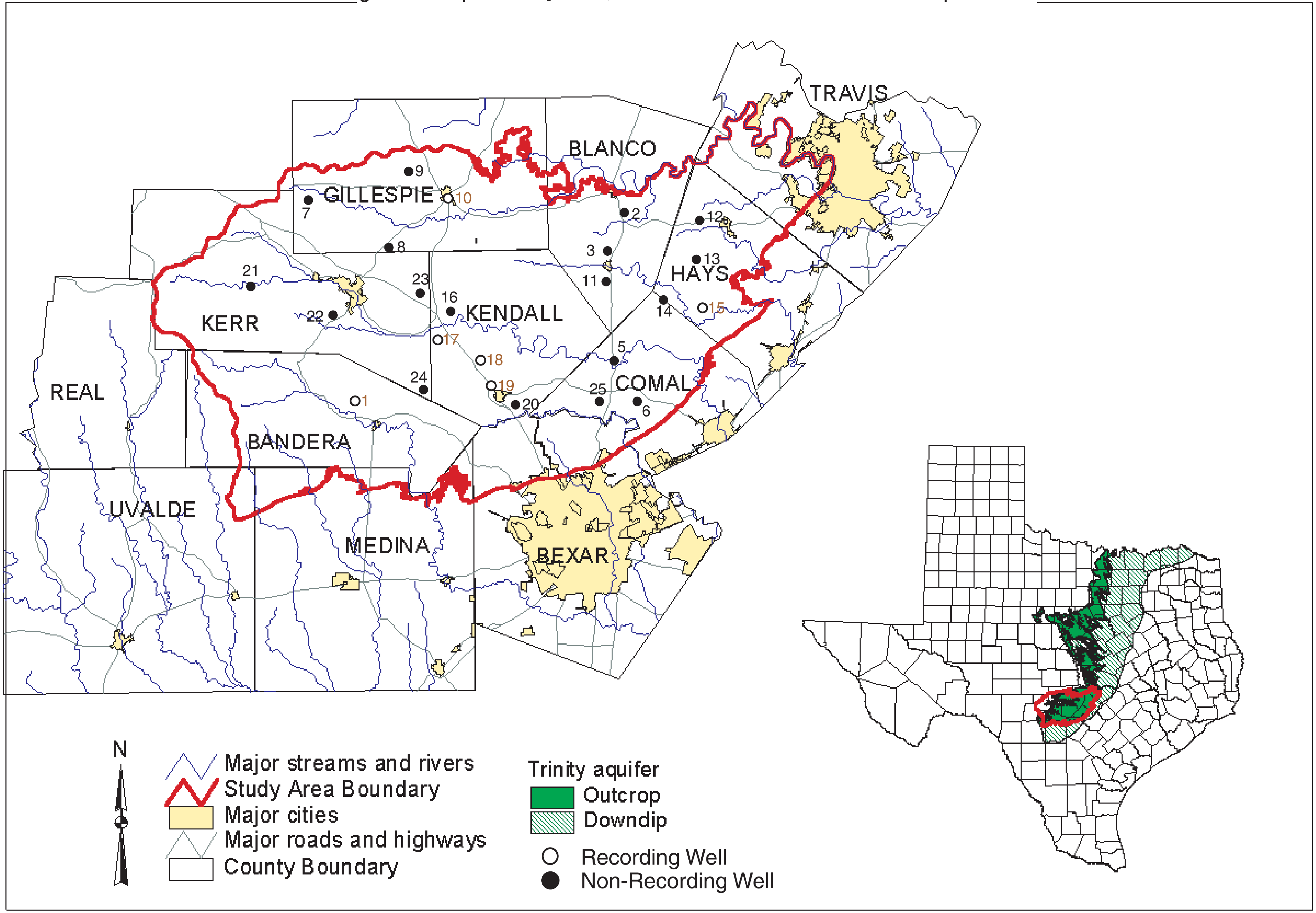
Introduction

The Trinity Aquifer in south-central Texas is an important and largely unique source of water in the Hill Country area of Texas that includes parts of Kendall, Kerr, Gillespie, Hays, Comal, Bexar, Travis, Medina, Blanco, and Uvalde counties (Fig. 1). All of the counties except Medina, Uvalde, Bexar, and Travis are included in the Hill Country Priority Groundwater Management Area (PGMA) as defined by the Texas Natural Resources Conservation Commission (TNRCC). All of the counties except Travis have Groundwater Conservation Districts (GCDs), or groups attempting to form GCDs. The GCDs in the region have formed the Hill Country Groundwater Conservation Districts Alliance (HCA) as an effective means of collaboration on conserving and preserving groundwater in the Trinity Aquifer.

Because of declining groundwater resources in the Trinity Aquifer PGMA, the Texas Water Development Board (TWDB) planned and completed a landmark investigation of the Trinity Aquifer in the region and produced a regional-level numerical groundwater flow model based on the MODFLOW model, McDonald and Harbaugh, (1988). The results of the investigation, Mace and others (2001), are being used for water planning by the three regional water planning groups (WPGs) that cover the Trinity Aquifer region—Regions K, L, and J—as well as by the HCA and the GCDs in the region.

A key issue in the TWDB investigation and MODFLOW modeling activity was the accurate determination of recharge to the Trinity Aquifer and specifically to the middle

Figure 1. Map of study area, adapted from Texas Water Development Board



Trinity Aquifer, which underlies the entire 10-county region. Because most investigators have estimated mean annual recharge rates to the Trinity Aquifer based on stream baseflows and produced estimates that varied from 4 to 11% of annual rainfall, it was decided to explore alternative methods of recharge determination.

The purpose of this research was to explore the utility of recharge calculation to the middle Trinity Aquifer in the region, based on water-level change and storativity determination in a network of observation wells scattered over the 10-county region.

Acknowledgements

The support of the Texas Water Resources Institute (TWRI) is gratefully acknowledged. This study was one of two research projects selected for funding by TWRI in 1998. Throughout the project, TWRI provided assistance and support in administering this effort and communicating results. In part, because of the support of TWRI in this study, the Edwards Aquifer Research & Data Center (EARDC) has been selected to receive a Texas Water Development Board (TWDB) grant from the Region J WPG through the San Antonio River Authority,. The grant enables the EARDC to install nine additional recording groundwater monitors within jurisdictions of groundwater conservation districts in the 10-county Trinity Aquifer region.

The authors wish to acknowledge the staff support of the, without which this study could not have been performed. The TWDB Groundwater Availability Section, headed by Robert Mace provided valuable support, advice, and expertise during the course of this study. The TWDB also provided used equipment and installation support for continuous (analog) water-level monitoring equipment at well sites near Dripping Springs, Kerrville, Fredericksburg, and Blanco, TX, and assisted Edwards Aquifer Research & Data Center staff in the installation of new continuous (digital) water-level monitoring equipment at wells sites near Wimberley, Boerne, and Medina, TX. Because this study had a strong field measurement program, the TWDB field staff support of Doug Coker, Hydrologist Assistant, was critically important. Coker’s careful training of graduate students and staff, encouragement, and ready assistance on all aspects of the field work is gratefully acknowledged.

This study could not have been performed without the cooperation of landowners who volunteered the use of their wells for monitoring. The authors thank the landowners for their interest in groundwater research and conservation.

Study Area

The study area includes parts of 10-counties in central Texas (Fig. 1), comprises about 4,500 square miles, and includes some of the surface drainage area of the Pedernales River, Barton Creek, Onion Creek, the Blanco River, the Guadalupe River, Cibolo Creek, and the Medina River.

The physiography of the study area is described in Mace and others (2000), Ashworth (1983), and Bluntzer (1992) among others, and is described as located on the southeastern margin of the Edwards Plateau or Texas Hill Country. The terrain is deeply dissected by erosion of rivers and creeks. Land-surface elevations vary from 2,400 feet above National Geodetic Vertical Datum (NGVD) in the west to about 800 feet in the east.

Much of the region contains alternating beds of weathered hard limestones and dolomites with soft marls and shales of the Glen Rose Limestone and forming a stair-step, karst topography.

For the purposes of this study, daily rainfall information was obtained from online databases from the National Climatic Data Center and in person (provisional records September – December, 2000) from the National Weather Service (NWS) at New Braunfels, TX for the following locations, scattered over the study region:

Table 1. --- Annual rainfall, in inches, for 1999, 2000, and for November-December, 2000 at eight locations in the study region

Location	1999	2000	Nov-Dec, 2000
Boerne, TX	18.67	44.37	10.16
San Antonio Intl AP	16.41	35.86	10.16
Fredericksburg, TX	17.32	30.51	7.06
Tarpley, TX	21.41	35.76	8.01
New Braunfels, TX	35.77	35.28	8.68
Johnson City, TX	16.90	39.40	10.78
Dripping Springs, TX	21.39	41.16	11.72
Kerrville 3 NNE	17.76	33.39	10.17
Average	18.55	37.97	

As seen, except for New Braunfels, TX, annual rainfalls for 1999 were substantially less than long-term mean annual rainfalls for the study region, in some areas approaching the low rainfalls during the drought of the 1950s. However, during November and December, 2000 significant rainfalls were recorded over the study region. The implications of these recorded rainfalls, for water levels in the study region, will be seen in the water-level data and recharge analyses given below.
The study area mean annual temperature ranges from 69° F to 63° F from west to east while lake surface evaporation is more than twice mean annual rainfalls.

Geology and Hydrogeology

Mace and others (2000), Ashworth (1983), and Bluntzer (1992) among others, have described the geology of the region as composed of Cretaceous rocks lying unconformably over Paleozoic rocks, (Fig. 2). Of particular concern in this study is the

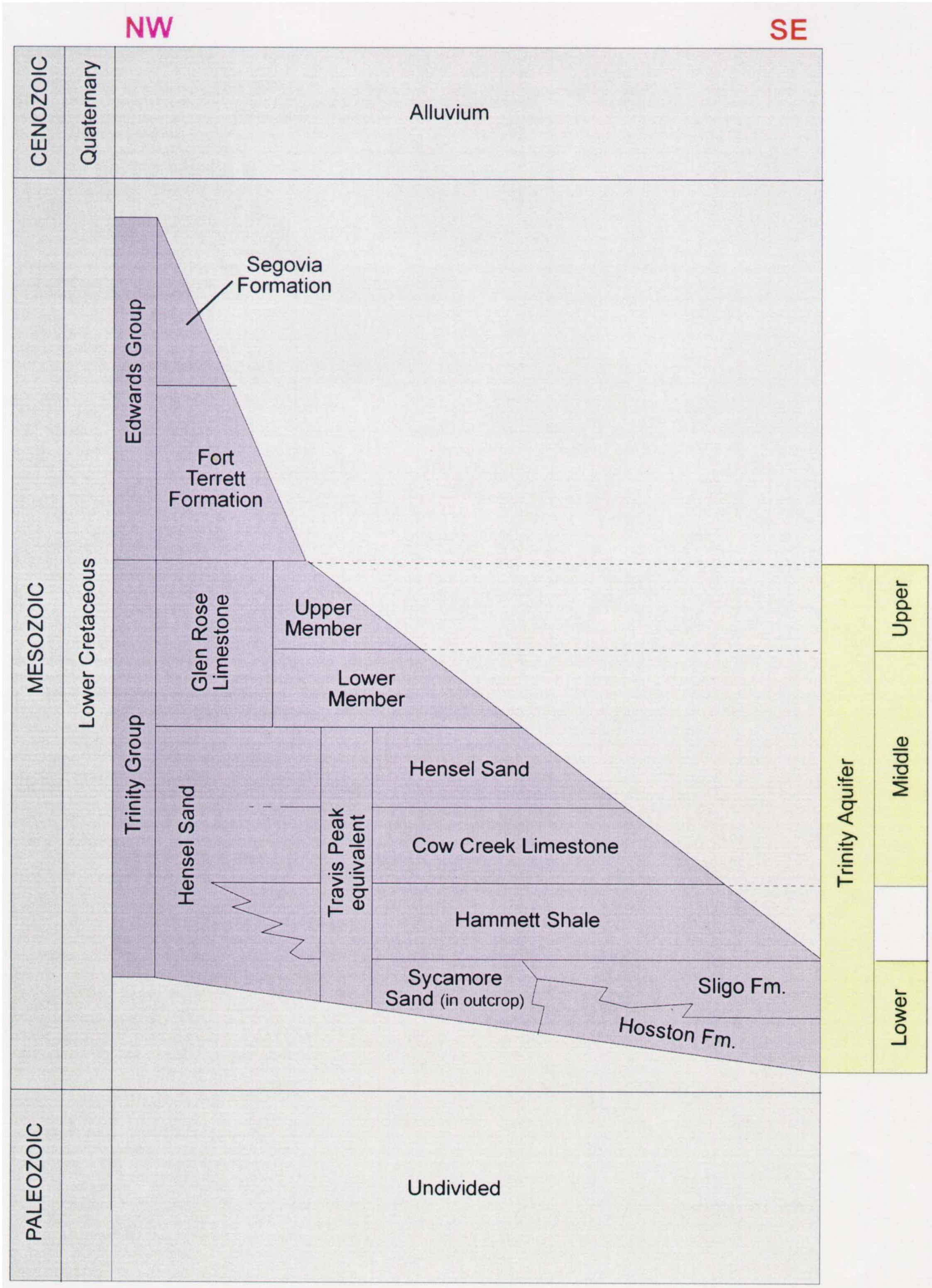


Figure 2. Hydrostratigraphy, after Mace and others, 2000

Trinity Aquifer and specifically the Middle Trinity Aquifer. As seen from (Fig. 2), the Middle Trinity Aquifer is composed of the Lower Member, Glen Rose Limestone, Hensel Sand, and Cow Creek Limestone depending on west to east location within the study area. Conceptually, the TWDB shaped the MODFLOW numerical groundwater flow model for the region in three layers (Fig. 3) — Edwards Group Limestones outcropping in the west, underlain by the Upper Trinity Limestones, from west to east, and finally underlain by the Middle Trinity Limestones, outcropping at places along the Medina, Guadalupe, and Blanco Rivers. The third model layer – the Middle Trinity Aquifer — is regionally continuous across the study area and is by far the most important aquifer, supplying water to about 85% of wells. In general, groundwater flows from areas of higher elevations topographically in the west to lower elevations in the east, Mace and others (2000).

Water Levels

Water levels in wells are fundamental to aquifer analysis and numerical modeling. As described below, the recharge determination method proposed in this report is based on spatial and temporal determination of water-level changes in a network of monitoring wells.

The TWDB and GCDs in the study region are making a good effort to obtain water levels in representative locations throughout the study region. About 120 TWDB monitoring well locations, most visited once a year or as needed, are registered and visited in the study region. Additional wells are monitored by the GCDs. A new HCA cooperative monitoring program has begun, with about 30-35 wells in the Middle Trinity Aquifer being monitored six times per year. Eight of these sites have daily continuous recorders, and some are equipped with telemetry. Occasionally, TWDB measures wells in the study region synoptically, that is all measurements are taken during a short time period of days in order to get a "snapshot" of regional aquifer levels. Synoptic water levels were obtained for the Trinity Aquifer in 1997 and 2000. When synoptic water level measurements are contoured (Fig. 4) a characterization or pattern of regional groundwater conditions is seen. The TWDB 2000 synoptic in the Trinity Aquifer captures a drought condition. Also seen from the contour map is the pattern of regional groundwater flow, as water flows from higher to lower water levels, where flow is perpendicular to gradient or downward change in water level elevation. All water levels are measured to NGVD datum. Circular-shaped contours describe groundwater "mounds" and "sinks." Closely spaced circles may indicate that groundwater flow is being directed toward an area of large groundwater pumpage.

The accuracy of water-level contour maps depends on the number of well datum points available for analysis, as well as such geology and hydrogeology controls as faults or streams.

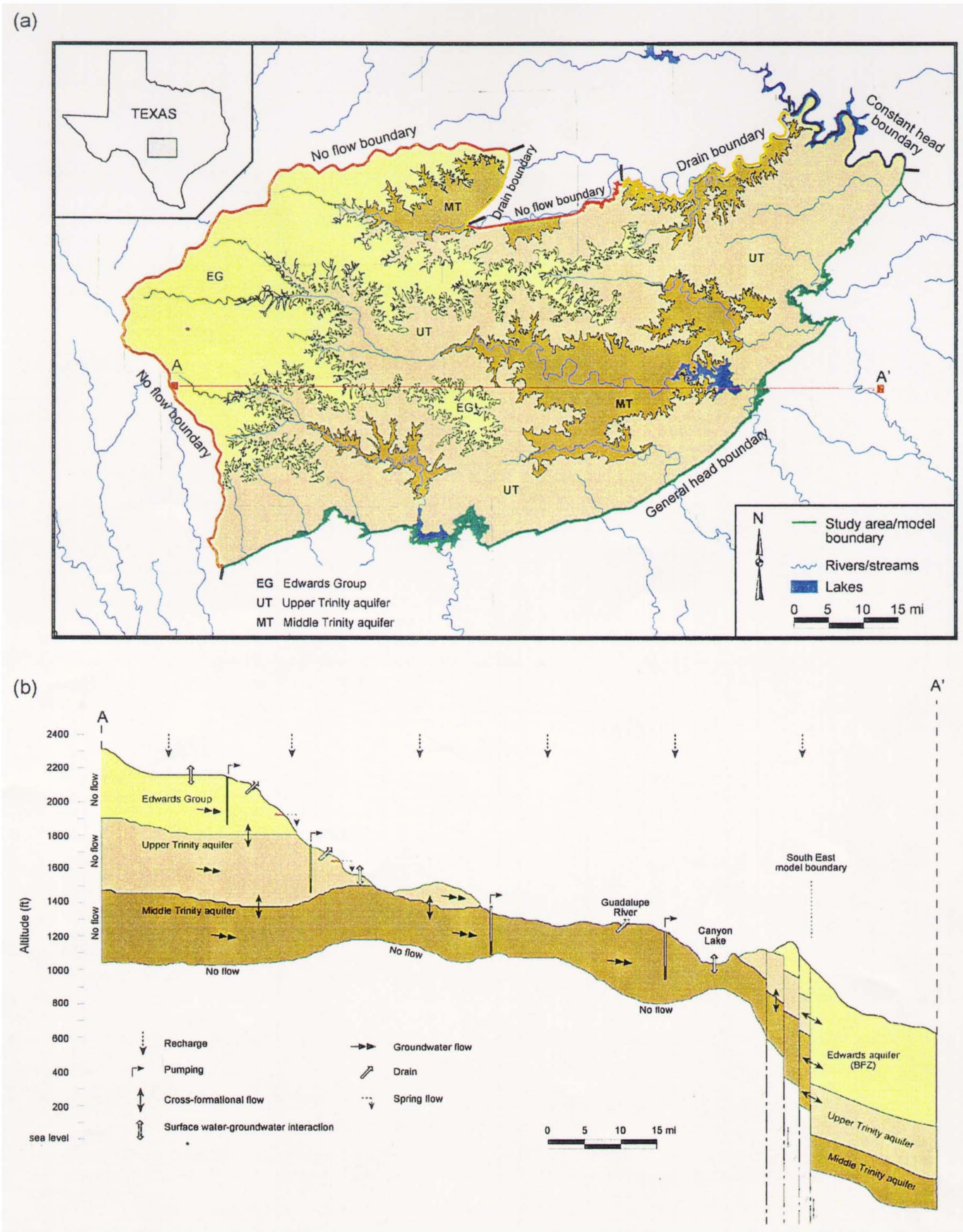
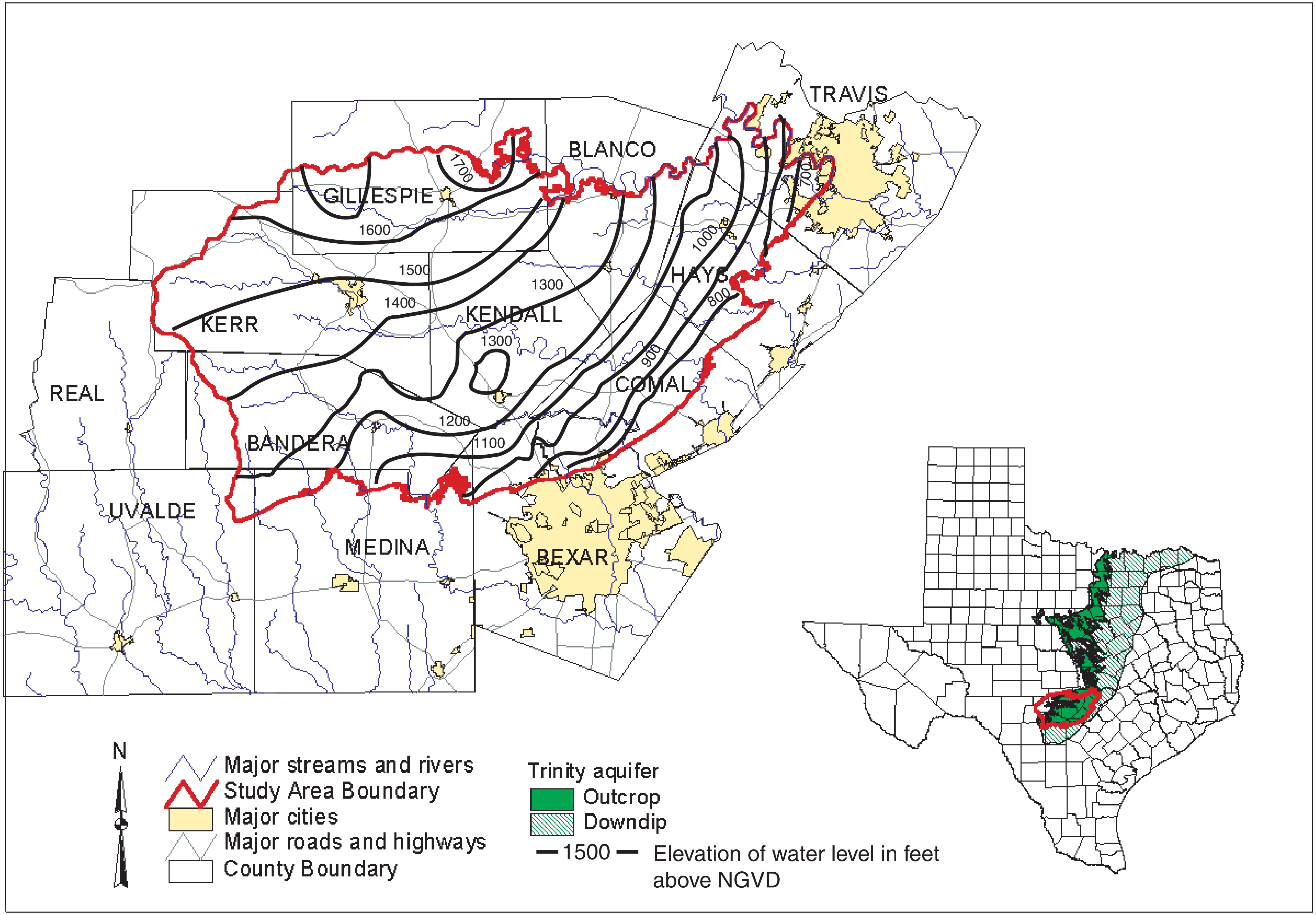


Figure 3. Conceptual model, after Mace and others, 2000

Figure 4. Estimated Middle Trinity Aquifer Synoptic water levels, August 2000. Adapted from Texas Water Development Board



Aquifer Recharge

The determination of aquifer recharge is a fundamental and mandatory requirement for any local or regional groundwater development program such as the groundwater availability program for the State of Texas. In a paper, Mace and others (2001) define groundwater availability as the amount of water that is available for societal use in Texas from an aquifer. These authors state that water produced from aquifers comes from three possible sources: recharge, storage, or flow from an adjacent, hydraulically connected aquifers. Not wishing to deplete aquifers, many groundwater managers will focus on average annual recharge as a safe long-term source of groundwater availability. Therefore, proper groundwater management places a strong emphasis on reliable aquifer recharge estimation.

Methods for Determination of Aquifer Recharge

Among the possible methods for aquifer recharge determination are: baseflow-recession method, Barnes (1939); temporal gravity surveys, Pool and Eychaner (1995); the water-budget method, Fetter (1994), numerical groundwater flow models, Mace and others (2000); streamflow differences; and, geochemical tracers, Halford and Mayer (2000).

Of these, the baseflow recession method is widely used in Texas, Muller and Price (1979) and the streamflow differences method is currently in use for the unique situation of the Edwards Aquifer in Texas. Model-determined recharge has been applied in the Trinity Aquifer, Mace and others (2000), as well as in Florida and other places. Geochemical tracers have been recommended, generally as an adjunct to other recharge determination methods. The temporal gravity survey method has been advanced as a surface geophysics approach with validity to groundwater investigations. This method, which requires somewhat expensive instrumentation, has been applied in an alluvial basin in Arizona with success, Pool and Eychaner (1995).

Fetter (1994) outlines the water budget method applied to the recharge area of an aquifer. This method calculates aquifer recharge as a residual by algebraically adding inputs, such as precipitation and surface-water flow, and outputs, such as evapotranspiration and groundwater discharge. For developed basins, the determination of additional groundwater recharge such as domestic and municipal use—less categories such as irrigation water evapotranspiration and waste treatment discharges to surface water—can greatly complicate the analyses. Fetter (1994) performed a sample error analysis for a typical water budget calculation and finds that calculations may be +/- 18% in error for some variables.

Recharge Determination Methods in the Trinity Aquifer

According to Mace and others (2000), the primary sources of recharge to the Trinity Aquifer in the study area are from rainfall on the outcrop (Fig. 3) and seepage losses through headwater creeks and lakes during high stages. The outcrops receiving direct recharge (Figs. 2 and 3) in the study area are the Upper Glen Rose Limestone, Lower Glen Rose Limestone, Hensel Sand, and the Edwards Group. According to Ashworth (1983), the Cow Creek Limestone and Lower Trinity Limestones are recharged by vertical leakage from overlying strata. Because overlying strata have interbeds of lower permeability marl, vertical downward leakage is often impeded and recharge can be laterally-directed to streams or highway cuts. This laterally directed recharge provides baseflow and springflow to gaining perennial streams in the study region. During episodes of significant rainfall—generally during the Fall-Winter period - higher water levels and laterally directed recharge sustain even the smallest headwater creeks that are incised in the overlying strata within the study region. This was the case following the Nov. – Dec. 2000 rainfalls (Table 1).

Mace and others (2000) summarize the work of several investigators within the last 20 years who have estimated recharge rates for the Middle Trinity Aquifer (Table 2.) They, based on model calculations, calculate that recharge to the Middle Trinity is only 1-2 percent of rainfall.

Table 2. Estimates of annual recharge as a percent of annual rainfall in the Study Area, from Mace and others (2000)

Investigations	Recharge as percent of Rainfall
Muller and Price (1979)	4 (1.5 for “availability recharge”)
Ashworth (1983)	4
Kuniansky (1989)	11
Bluntzer (1992)	7
Mace and others (2000)	6.6
Investigations using groundwater models	
Kuniansky and Holligan (1994)	7
Mace and others (2000)	4

Most of the above methods use stream baseflow to estimate recharge. Fetter (1994) describes the methodology, which assumes that baseflow to a river, or creek is equivalent to groundwater discharge. Using streamflow records and baseflow recessions graphed on semi-logarithmic paper to show baseflow recessions as straight lines (or more recently using computer programs for automated hydrograph separation techniques), an estimate is made of annual potential groundwater discharge. If a series of streamflow stations exist on rivers and creeks in the area, refinement of apparent groundwater discharge is made. Apparent recharge to the aquifer in hydraulic communication with rivers and creeks is obtained by successive year differences of annual apparent groundwater discharge. The assumption is that non-discharged groundwater is recharge to the aquifer. The stream baseflow recharge method has been widely used since at least 1921 in West Sussex, England and since 1939 in the United States.

In the semi-arid Texas Hill Country, cycles of dry years followed by normal or even wet years, e.g. 1999-2000, cause baseflow in rivers and creeks to be irregular and cease in some years. In wet years, baseflow representing aquifer discharge can continue for months. This irregular nature of rainfall-baseflow causes special problems for recharge calculations that otherwise would be reasonably satisfactory in more humid areas. In general, baseflow is assumed to be aquifer recharge as a general estimate. As pointed out by Halford and Mayer (2000), the validity of groundwater discharge and recharge estimates from stream discharge data is difficult to test, because these quantities cannot be measured directly. Bluntzer (1992), using baseflow from an area of about 3,500 square miles (75% of our study area), calculated long-term mean annual baseflow from area rivers and creeks. He found a recharge rate of 6.7% of mean annual precipitation in the area, or 369,100 acre-ft/year. He also noted that baseflow in the area was highly variable over time.

The baseflow analyses assume that there are no consumptive uses of groundwater in the vicinity such that all groundwater discharge appears as baseflow in streams. Bluntzer (1992), recognizing that human impacts on baseflow such as near-stream groundwater pumpage, stream diversions and return flows and in-stream retention structures can change an estimate of groundwater discharge. He reduced his annual recharge estimate from about 7% to 5%. The analysis also assumes that a sufficient network of streamflow measuring stations exists or that special measurements can be made with current meters. All major rivers in our study area are measured for daily streamflow by the U.S. Geological Survey (USGS). However, multiple sites per basin are not common and many smaller creeks are not measured at all. Kuniansky and Holligan (1994) reduced their recharge estimate from 11% to 7% to improve model calibration because they believed their analysis did not contain all local rivers and creeks recharging the Trinity Aquifer. Mace and others (2000) point out that all accurate stream baseflow methods underestimate recharge because they exclude the component of recharge that follows the regional flow path i.e. does not appear as baseflow.

Note that two investigations found that a lower (by 2-4%) recharge value was necessary as a result of numerical model calibration.

The TWDB, Mace and others (2000) noted that some of the values in Table 2 are influenced by high or low periods of annual rainfall included within the period of analysis. This led the TWDB team to use a computer hydrograph separation technique to estimate baseflow for the period 1940 to 1990, then adjust baseflow parameters to match Ashworth (1983) and Kuniansky (1989) baseflow values where measured. The analysis yielded a recharge rate of 6.6% of mean annual precipitation. Using the 11 available sub-basin baseflows from Kuniansky (1989), spatial distribution of baseflow over the MODFLOW study area was made using a mean annual rainfall map based on 37 precipitation stations, and subsequently determined recharge coefficients for all model grids was made. Because the Kuniansky (1989) recharge values were high, they were adjusted down by 0.45 to match the other typical values in Table 2.

Eliminating the high and low values of Table 2 leaves a range of average annual recharge rates of from 4 to 7% of mean annual precipitation, depending on investigator or the difference between calculated baseflow-derived values and model-derived values. Over the 4,500 square miles of the study region, assuming a 30-inch annual precipitation, this 3% difference represents a plus or minus uncertainty in study area recharge of 216,000 ac ft per year. If from Table 2, the value of 5.5% for recharge estimation is judged to be an average value, average annual recharge for the Trinity Aquifer study region can only be estimated plus or minus about 30%.

In a recent paper, Halford and others (2000) examine problems associated with estimating groundwater discharge and recharge from streamflow records. In a study of 13 field sites, mostly in the eastern United States, they conclude that the baseflow method of recharge determination can be a poor tool for estimating groundwater discharge and recharge. These authors advise multiple, alternative methods of estimation be used because of the uncertainty associated with any one technique. They point out that numerical groundwater flow models, such as Mace and others (2000) can give an estimate of recharge if hydraulic conductivity estimates from aquifer tests are properly constrained. They also suggest use of conservative geochemical tracers to assist in quantification of the groundwater component of stream discharge.

Proposed Recharge Method for the Middle Trinity Aquifer

As mentioned above, water-level measurements at a network of groundwater observation wells within the Trinity Aquifer and, specifically, the widely-used Middle Trinity Aquifer, have much utility in groundwater analyses. If a fairly dense network of monitoring wells is available in a region, water level change and aquifer properties can be used to estimate water removed from or added to an aquifer. Fetter (1994) explains that when the head in a saturated aquifer or confining unit changes, water will be either stored or expelled. Fetter defines the storage coefficient or storativity, S, as the volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head. S is a dimensionless quantity and is generally obtained from 2-well aquifer tests, Fetter (1994). If an aquifer is unconfined, storativity is approximated by the specific yield, S_y. Mace and others (2000) found that values of $S = 1 \times 10^{-7}$ and $S_y = 0.8 \times 10^{-3}$ worked best for model calibration for the Middle Trinity Aquifer.

According to Fetter (1994), the volume of water drained or added from an aquifer as the head lowers or rises may be found from the formula:

$$V_w = S\ A\ \Delta h \qquad \text{Eq. (1)}$$

where

V_w	is the volume of water drained or added in acre-feet (AF)
S	is the storativity, dimensionless
A	is the surface area overlying the aquifer unit, in acres
Δh	is the average decline or increase in head, ft

Therefore, if water level change Δ h can be determined spatially over the aquifer unit of concern, and if S can be determined satisfactorily, a calculation of the volume of water drained or added is possible by a simple calculation. The surface area, A can be determined from topographic maps. Further, if portions of the surface area can be weighted by variation in S values and if Δ h for different time periods and location within the study area can be determined from a well-level monitoring network, a spatially and temporally variable calculation of V_w can be made within year, annually, and for long-term average annual values. Positive values of V_w are net recharge, while negative values of V_w are net aquifer depletion from pumpage and natural withdrawals such as springs, cross-formational flow exchange, rejected groundwater flow or baseflow in rivers and creeks and evapotranspiration.

Data Collection

Data collection for this project focused on the quantities needed to apply Eq.(1.) Specifically, these are area, A, representing the surface area overlying the Middle Trinity Aquifer and estimated to be 4,500 mi^2 , of which about 900 mi^2 is outcrop area, and S, storativity values, determined from 2-well aquifer tests and reported in Mace and others (2000). Spatial and temporal determination of water-level changes were obtained from a network of recording and non-recording wells in the Middle Trinity Aquifer (Fig. 1).

Storativity and Specific Yield Values for the Middle Trinity Aquifer

According to Mace and others (2000), 10 2-well aquifer tests were performed or compiled to define aquifer storativity, S, including values for the Hensel Sand and Lower Glen Rose and Cow Creek formations in Gillespie County (2 values), Blanco County (3 values), Hays County (3 values), Comal County (1 value), and Bandera County (1 value). These observed S values had a fairly wide range of from 8×10^{-7} to 7×10^{-4} . With outliers removed, the average value of S is about 3.5×10^{-4} . These authors suggested an S value of 1×10^{-7} and specific yield, $S_y = 8 \times 10^{-4}$ as suitable for modeling calculations. Portions of the Middle Trinity Aquifer are under confined conditions where storativity, S is applicable while other areas, particularly outcrop areas, are unconfined, where specific yield, S_y is applicable. As pointed out by Mace (2001), in a fractured limestone aquifer like the Trinity Aquifer, fracture porosity controls what specific yield can be and its variation. Large variation in specific yield and storativity can occur in the Trinity Aquifer because fracturing can be highly variable and connectivity of fracturing can be variable and unknown, many times complicated by sparse data. Because the water-level technique for recharge depends on highly variable storativity and specific yield values, considerable uncertainty over large areas—such as the Trinity Aquifer PGMA—may be seen in recharge calculation results by this method.

Over small areas, storativity values may be less variable. For example, a set of six multiple well aquifer tests in the Trinity Aquifer in Bexar County was reported by LBG-Guyton Associates (2001). Although much variation was found in aquifer transmissivity for this study, the model-calibrated storativity , S, was 6×10^{-5} and was consistent with values obtained from aquifer tests and with the TWDB MODFLOW model assignments, Mace and others (2000).

Water-Level Monitoring Network

Water levels were obtained at 23 Middle Trinity Aquifer wells during the period 1999-2000 (Fig. 1). All sites were visited at least 6 times per year.

Six recording sites were operated in Gillespie, Hays, Bandera, and Kendall counties. Three of the six recording well sites are located in Kendall County with one each operated by the EARDC at Southwest Texas State University, the U.S. Geological Survey (USGS), and the Texas Water Development Board. The recording site in Gillespie County is operated by the Hill Country Underground Water Conservation District with equipment installed by TWDB. Recording sites in Hays, Kendall and Bandera counties are operated by EARDC in collaboration with local GCDs. Four of the six recording sites were installed by EARDC students and staff supported by TWDB and local GCD personnel, in order to support the investigation described in this report. They will remain in place after the study is completed. EARDC sites have data transmitted by telemetry to Southwest Texas State University. The information is updated weekly on the EARDC web site, http://eardc.swt.edu/Trinity/trinity.html. The USGS site in Kendall County is telemetered by satellite and is updated on the USGS web site, http://tx.usgs.gov.

The non-recording well sites were all established by TWDB prior to or as a part of this present investigation. Tables 3 and 4 and Fig. 1 describe location, characteristics, and data for these sites. As mentioned, the non-recording sites are visited at least 6 times per year. Unfortunately, two well sites went out of service during the first part of 1999 and were eliminated from use in this study.

Figures 5 and 6 for Hays County well sites can be used to illustrate water level information from recording and non-recording well sites. Figure 6 is a graph of daily well levels and daily NWS rainfalls at Dripping Springs, 6 E for well number 57-64-705 as registered with TWDB. Water level is obtained by a calibrated pressure transducer and verified by independent measurement using a steel tape or electronic tape (E-line). Note that the pressure transducer malfunctioned during two periods, but that visits were made to obtain supplementary measurements. Water levels during the two-year period varied from about 80 feet below land surface to about 140 feet below land surface. This recorded water level data is similar to other sites in the study region, and shows seasonal drops during summer months and rises during winter months when pumpage and evapotranspiration are lower. The effects of rainfall periods on water level rises are also seen, especially the large rise following the Nov- Dec, 2000 rainfalls. Overall, due to lower than normal rainfalls during 1999-2000, a pattern of general water level decline is seen.

Figure 5, well number 57-56-710 is located in Hays County about 8 miles north of the recording well, 57-64-705, is similar in pattern to the recording well, but does not include the winter recovery during Nov. 1999 – June 2000. The impact of the Nov. – Dec. 2000 rainfalls is seen at both sites.

Table 3. Water level data collected at Network Monitoring Wells, 1999-2000

No.	County	State Well Number	Date	Depth from Land Surface	Depth from MP	Measuring agency	Measurement Method	Remarks	Well use	Comments
	Bandera	69-14-608	4/7/99	34.09		3	2		U	
	Bandera	69-14-608	5/18/99	34.19	36.89	3	2		U	
	Bandera	69-14-608	7/6/99	33.59	36.29	3	2		U	
	Bandera	69-14-608	8/18/99	34.13	36.83	3	2		U	
1	Bandera	69-14-608	10/14/99	34.97	37.67	3	2		U	Stakes in ground
	Bandera	69-14-608	1/12/00	35.63	38.33	1	2		U	
	Bandera	69-14-608	1/25/00	34.74						Recorder installed
	Bandera	69-14-608	8/2/00	35.20						
	Bandera	69-14-608	12/21/00	35.75						
	Blanco	57-53-305	3/31/99	209.41	209.91	3	2		U	
	Blanco	57-53-305	5/17/99	212.45	212.95	3	2		U	Steel tape 212.33 from MP
	Blanco	57-53-305	7/8/99	214.07	214.57	3	1		U	E-line 214.57
	Blanco	57-53-305	8/17/99	214.90	215.40	3	1		U	
2	Blanco	57-53-305	10/15/99	214.19	214.69	3	1		U	E-line 215.05 from MP
	Blanco	57-53-305	1/12/00	215.48	215.98	3	1		U	
	Blanco	57-53-305	2/9/00	216.60						
	Blanco	57-53-305	8/1/00	219.20						
	Blanco	57-53-305	9/26/00	220.54						
	Blanco	57-53-305	12/20/00	212.38						
	Blanco	57-61-219	3/31/99	41.87	45.52	3	1		P	City may pump periodically
	Blanco	57-61-219	5/17/99	44.42	48.07	3	1		P	
3	Blanco	57-61-219	7/7/99	49.89	53.44	3	1		P	
	Blanco	57-61-219	8/17/99	55.05	58.70	3	1		P	
	Blanco	57-61-219	10/15/99	120.70	124.35	3	1	22	P	Well possibly pumped recently--need to call
	Blanco	57-61-219	1/12/00			3		40	P	Well destroyed
	Blanco	57-53-614	3/31/99	272.09	272.99	3	1		U	Will set up recorder
	Blanco	57-53-614	5/17/99	276.3	277.2	3	1		U	
	Blanco	57-53-614	6/10/99	291.98						
	Blanco	57-53-614	7/7/99	277.34	278.24	3	3		U	Steel tape broken, needs new MP
	Blanco	57-53-614	8/17/99	305.09	306.59	3	1	3	U	Nearby well pumped a lot recently, needs new MP
4	Blanco	57-53-614	10/15/99	355.74	357.24	3	1	3	U	New MP = +1.50
	Blanco	57-53-614	1/12/00	300.10	301.60	3	1		U	
	Blanco	57-53-614	4/10/00	298.25						
	Blanco	57-53-614	4/19/00	300.55						
	Blanco	57-53-614	8/1/00	319.90						
	Blanco	57-53-614	12/20/00	319.92						
	Comal	68-06-709	3/31/99	32.99	33.99	3				
	Comal	68-06-709	5/4/99	32.66	33.66	3	1		U	
5	Comal	68-06-709	5/19/99	32.53	33.53	3	1		U	
	Comal	68-06-709	7/6/99	32.49	33.49	3	1		U	
	Comal	68-06-709	8/18/99	34.03	35.03	3	1		U	Casing open

Table 3. Water level data collected at Network Monitoring Wells, 1999-2000 (continued)

No.	County	State Well Number	Date	Depth from Land Surface	Depth from MP	Measuring agency	Measurement Method	Remarks	Well use	Comments
	Comal	68-06-709	10/14/99	35.65	36.65	3	1		U	Casing open
5	Comal	68-06-709	1/13/00	36.94	37.94	3	1		U	Well has locking cap now
	Comal	68-06-709	8/3/00	38.10			1		U	
	Comal	68-06-709	12/21/00	33.02						
	Comal	68-13-806	3/31/99	275.57	276.42	3				
	Comal	68-13-806	5/19/99	306.9	307.75	1	2		P	
	Comal	68-13-806	7/6/99	308.67	309.72	3	2	4	P	Pumped Recently
25	Comal	68-13-806	8/18/99	326.58	327.43	3	2		P	
	Comal	68-13-806	10/14/99	319.85	320.70	3	2		P	
	Comal	68-13-806	2/24/00	331.90			2		P	
	Comal	68-13-806	8/8/00	333.05						
	Comal	68-13-806	12/21/00	276.20						
	Comal	68-14-407	4/21/99	370.03	371.83	1				
	Comal	68-14-407	5/19/99	393.02	394.82	3	2		P	E-line hangs at 345'
	Comal	68-14-407	7/6/99			3	2		P	hangs @ 345'
6	Comal	68-14-407	8/18/99	420.07	421.87	3	2	44	P	E-line hangs at 345'
	Comal	68-14-407	10/14/99			3	1		P	
	Comal	68-14-407	1/13/00	425.60	427.40	3	1	47	P	Spotty tape, no measurement
	Comal	68-14-407	12/21/00	362.02			1		P	
	Gillespie	56-47-908	4/19/99	294.77	296.77	3				
	Gillespie	56-47-908	5/17/99	293.91	295.91	3	1		H	
	Gillespie	56-47-908	7/7/99	294.70	296.70	3	1		H	
	Gillespie	56-47-908	8/19/99	296.63	298.63	3	1		H	
7	Gillespie	56-47-908	10/15/99	295.50	297.50	3	1		H	
	Gillespie	56-47-908	1/14/00	294.35	296.35	3	1		H	
	Gillespie	56-47-908	3/24/00	294.01			1		H	
	Gillespie	56-47-908	7/14/00	295.32						
	Gillespie	56-47-908	10/12/00	294.38						
	Gillespie	56-56-602	4/21/99	141.04	141.94	3				
	Gillespie	56-56-602	5/18/99	140.4	142.3	3	1		S	
	Gillespie	56-56-602	7/7/99	140.77	142.67	3	1	4	S	Pumped Recently
8	Gillespie	56-56-602	8/19/99	141.30	143.20	3	1		S	Well not pumped in 3 days
	Gillespie	56-56-602	10/15/99	141.65	143.55	3	1		S	
	Gillespie	56-56-602	1/14/00	142.52	144.42	3	1		S	
	Gillespie	56-56-602	3/24/00	141.85			1		S	Gate now has lock on it--contact owner
	Gillespie	56-56-602	7/17/00	142.60						
	Gillespie	56-56-602	10/12/00	142.90						
	Gillespie	56-56-602	12/18/00	142.25						
	Gillespie	57-41-403	4/19/99	54.33	54.13	3				
9	Gillespie	57-41-403	5/17/99	54.08	53.88	3	1		H	
	Gillespie	57-41-403	7/7/99	54.04	53.84	3	1		H	

Table 3. Water level data collected at Network Monitoring Wells, 1999-2000 (continued)

No.	County	State Well Number	Date	Depth from Land Surface	Depth from MP	Measuring agency	Measurement Method	Remarks	Well use	Comments
	Gillespie	57-41-403	8/19/99	54.00	53.80	3	1		H	
	Gillespie	57-41-403	10/15/99	54.15	53.95	3	1		H	
	Gillespie	57-41-403	1/14/00	55.33	55.13	3	1		H	
9	Gillespie	57-41-403	3/27/00	55.04			1		H	
	Gillespie	57-41-403	7/17/00	55.69						
	Gillespie	57-41-403	10/13/00	56.28						
	Gillespie	57-41-403	12/18/00	56.63						
	Gillespie	57-42-722	4/19/99	20.36		3				
	Gillespie	57-42-722	5/17/99	20.83	23.43	3	1		U	
	Gillespie	57-42-722	5/24/99	21.85	23.35	3	1		U	send copy to Paul Tybor
10	Gillespie	57-42-722	7/7/99	21.12	23.62	3	1		U	
	Gillespie	57-42-722	8/2/99	25.40	26.90	3	4		U	
	Gillespie	57-42-722	8/19/99	29.37	30.87	3	1		U	
	Gillespie	57-42-722	10/15/99	27.39	28.89	3	1		U	K+B=29.31
	Gillespie	57-42-722	1/12/00	24.45	25.95	1	1		U	k+b=27.32
	Hays	57-47-902	9/24/98	19.10	21.00	1	1		U	
	Hays	57-47-902	3/29/99	19.38		3	2		U	
	Hays	57-47-902	5/17/99	20.86	22.76	3	1		U	
	Hays	57-47-902	7/8/99	19.05	20.95	3	1		U	B-K=20.81
11	Hays	57-47-902	8/2/99	19.47	21.37	3	1		U	K+B=18.99
	Hays	57-47-902	8/17/99	20.28	22.18	3	1		U	K+B=19.45
	Hays	57-47-902	10/16/99	23.00	24.90	3	1		U	K+B=20.20. 35 ft. left
	Hays	57-47-902	1/12/00	170.86	172.76	1	1		U	K+B=23.01, 23ft left
	Hays	57-47-902	1/18/00			1	1		U	
	Hays	57-55-401	3/29/99	292.09	293.29	3	1		U	
	Hays	57-55-401	5/17/99	301.14	302.34	3	1		P	
	Hays	57-55-401	7/8/99	305.28	305.48	3	1		P	
	Hays	57-55-401	8/17/99	311.87	313.07	3	1		P	
	Hays	57-55-401	10/16/99	328.20	329.40	3	1		P	
12	Hays	57-55-401	1/12/00	327.33	328.53	3	1		P	
	Hays	57-55-401	4/28/00	334.22			1		P	
	Hays	57-55-401	7/8/00	341.54						
	Hays	57-55-401	8/2/00	346.92						
	Hays	57-55-401	12/2/00	341.45						
	Hays	57-55-401	12/16/00	337.60						
	Hays	57-56-710	4/7/99	173.73	174.73	1				
	Hays	57-56-710	5/17/99	177.89	178.89	3	2		H	15:49
13	Hays	57-56-710	7/8/99	183.20	184.20	3	1		H	Tape hangs in several places
	Hays	57-56-710	8/17/99	188.88	189.88	3	1		H	
	Hays	57-56-710	10/16/99	194.22	195.22	3	1		H	
	Hays	57-56-710	1/12/00	194.65	195.65	3				

Table 3. Water level data collected at Network Monitoring Wells, 1999-2000 (continued)

No.	County	State Well Number	Date	Depth from Land Surface	Depth from MP	Measuring agency	Measurement Method	Remarks	Well use	Comments
	Hays	57-56-710	4/28/00	201.10			1		H	
	Hays	57-56-710	7/8/00	203.75						
	Hays	57-56-710	8/2/00	204.30						
13	Hays	57-56-710	9/2/00	208.50						
	Hays	57-56-710	10/27/00	205.69						
	Hays	57-56-710	12/2/00	171.88						
	Hays	57-56-710	12/16/00	169.65						
	Hays	57-56-710	12/29/00	167.37						
	Hays	57-63-703	3/31/99	166.46	167.09	3				
	Hays	57-63-703	5/17/99	168.53	169.13	3	1		U	Lost e-line, tape hangs near water surface
	Hays	57-63-703	7/8/99	168.18	168.78	3	1		U	spotty tape
	Hays	57-63-703	8/17/99	168.15	168.75	3	1		U	
14	Hays	57-63-703	10/16/99	169.38	168.98	3	1		U	
	Hays	57-63-703	1/12/00	169.43	170.03	3	1		U	
	Hays	57-63-703	4/28/00	169.96			1		U	
	Hays	57-63-703	7/8/00	170.30						
	Hays	57-63-703	12/16/00	169.05						
	Hays	57-64-705	3/29/99	80.25	82.25	1				
	Hays	57-64-705	5/17/99	84.21	86.21	3	1		U	
	Hays	57-64-705	7/8/99	97.21	99.21	3	1		U	
	Hays	57-64-705	8/17/99	109.87	111.87	3	1		U	14:34
	Hays	57-64-705	10/16/99	130.24	132.24	3	1		U	11:00
	Hays	57-64-705	11/18/99	129.08	131.08	3	1		U	
	Hays	57-64-705	1/12/00	120.98	122.98	3	1		U	
	Hays	57-64-705	4/8/00	106.82			1		U	
15	Hays	57-64-705	4/28/00	103.33						
	Hays	57-64-705	7/8/00	108.14						
	Hays	57-64-705	7/22/00	119.10						
	Hays	57-64-705	8/4/00	125.95						
	Hays	57-64-705	10/26/00	140.75						
	Hays	57-64-705	11/9/00	137.98						
	Hays	57-64-705	12/1/00	127.88						
	Hays	57-64-705	12/16/00	121.08						
	Hays	57-64-705	12/27/00	116.41						
	Hays	57-64-705	12/29/00	115.45						
	Kendall	57-58-706	4/7/99	98.91	98.11	3				
	Kendall	57-58-706	5/19/99	100.56	99.76	3	1		H	
16	Kendall	57-58-706	7/6/99	102.07	101.27	3	1		H	Wasps in shed
	Kendall	57-58-706	8/18/99	104.59	103.79	3	1		H	
	Kendall	57-58-706	10/14/99	108.41	107.61	3	1		H	
	Kendall	57-58-706	1/13/00			3	1		H	

Table 3. Water level data collected at Network Monitoring Wells, 1999-2000 (continued)

No.	County	State Well Number	Date	Depth from Land Surface	Depth from MP	Measuring agency	Measurement Method	Remarks	Well use	Comments
16	Kendall	57-58-706	8/1/00	120.10				61	H	Gate now has lock on it--contact owner
	Kendall	57-58-706	12/16/00	115.10						
	Kendall	68-01-314	5/19/99	100.07		1				
	Kendall	68-01-314	7/6/99	105.59	104.09	3	4			K+B=100.07; tape =99.94
17	Kendall	68-01-314	8/18/99	111.34	112.84	3	1		U	K+B=103.66
	Kendall	68-01-314	10/14/99	123.11	121.61	3	1		U	
	Kendall	68-01-314	1/13/00	114.85	116.35	3	1		U	
	Kendall	68-01-314	12/20/00	108.58			1		U	Fence was built around shed to allow access
	Kendall	68-02-609	5/19/99	98.38	99.63	3				
	Kendall	68-02-609	7/6/99	102.21	103.46	3	4		U	Taped 99.52 from MP
18	Kendall	68-02-609	8/18/99	111.75	113.00	3	1		U	102.21 was the recorder reading
	Kendall	68-02-609	10/14/99	120.10	121.35	3	1		U	111.90 = recorder reading, 111.92 = K+B
	Kendall	68-02-609	1/13/00	110.19	111.44	3	1		U	120.25 = recorder reading @ 16:40, 120.29 = K+B
	Kendall	68-02-609	12/20/00	84.09			1		U	110.37 = recorder reading @13:35, 110.35 = K+B
	Kendall	68-11-417	4/5/99	236.45		1				
	Kendall	68-11-417	5/19/99	241.34	243.15	3	2		U	
	Kendall	68-11-417	7/6/99	254.93	256.53	3	2		U	Don't have MP
	Kendall	68-11-417	8/18/99	271.65	273.25	3	2		U	
	Kendall	68-11-417	10/14/99			3	2		U	
19	Kendall	68-11-417	12/10/99	281.93	283.53	1	2	42	U	Well not accessable--blow out pipe in well
	Kendall	68-11-417	1/13/00	247.32	248.92	3	2		U	
	Kendall	68-11-417	1/24/00	278.05			2		U	
	Kendall	68-11-417	5/3/00	283.51						
	Kendall	68-11-417	8/2/00	287.52						
	Kendall	68-11-417	12/20/00	258.39						
	Kendall	68-11-715	4/5/99	212.96		1				
	Kendall	68-11-715	5/19/99	217.22	217.22	3	1		S	
	Kendall	68-11-715	7/6/99	220.40	220.40	3	1		S	
	Kendall	68-11-715	8/18/99	227.18	227.18	3	1		S	Spotty
20	Kendall	68-11-715	10/14/99	229.90	229.90	3	1		S	Spotty
	Kendall	68-11-715	1/13/00	246.34	246.34	3	1		S	Spotty
	Kendall	68-11-715	1/24/00	227.91			1	4	S	Livestock show in Progress
	Kendall	68-11-715	2/14/00	227.85						
	Kendall	68-11-715	8/2/00	229.92						
	Kendall	68-11-715	12/20/00	218.95						
	Kerr	56-62-408	4/21/99	308.25	309.75	3				
	Kerr	56-62-408	5/18/99	306.68	308.18	3	1		I	
21	Kerr	56-62-408	7/7/99	315.17	316.67	3	1		I	spotty tape, hangs
	Kerr	56-62-408	8/20/99	323.90	324.40	3	1		I	Spotty
	Kerr	56-62-408	10/15/99	323.50	325.00	3	1		I	
	Kerr	56-62-408	1/13/00	320.53	321.03	3	1		I	

Table 3. Water level data collected at Network Monitoring Wells, 1999-2000 (continued)

No.	County	State Well Number	Date	Depth from Land Surface	Depth from MP	Measuring agency	Measurement Method	Remarks	Well use	Comments
	Kerr	56-63-916	4/12/99	318.00		6	1		I	
	Kerr	56-63-916	5/3/99	311		6	2		U	
	Kerr	56-63-916	5/18/99	309.01	311.01	3	2		U	
	Kerr	56-63-916	6/3/99	315.2	317.2	3	1		U	
22	Kerr	56-63-916	7/6/99	334.94	336.94	3	1		U	
	Kerr	56-63-916	8/2/99	340.71	342.71	3	1		U	
	Kerr	56-63-916	8/18/99	352.19	354.19	3	1		U	K+B=340.82
	Kerr	56-63-916	10/14/99			3	1		U	Float stuck
	Kerr	56-63-916	10/21/99	364.45	366.45	3	1	61	U	Well locked with non-TWDB lock
	Kerr	56-63-916	1/12/00	338.40	340.40	1	1		U	
	Kerr	57-57-703	4/21/99	96.47	98.87	3	1		U	
	Kerr	57-57-703	5/19/99	97.6	99	3	2		I	
23	Kerr	57-57-703	7/6/99	99.90	101.40	3	2		I	
	Kerr	57-57-703	8/18/99	109.02	111.52	3	2		I	New MP from pipe top is +2.50
	Kerr	57-57-703	10/14/99	225.06	222.56	3	2		I	
	Kerr	57-57-703	1/13/00	109.99	112.49	3	2	2	I	well is pumping
	Kerr	68-09-501	4/19/99	233.54	234.94	1	2		I	
	Kerr	68-09-501	5/18/99	233.76	235.16	3	2		H	
	Kerr	68-09-501	7/7/99	237.95	239.35	3	2		H	
24	Kerr	68-09-501	8/18/99	240.27	241.67	3	2		H	Not pumped for 13 hours prior to measurement
	Kerr	68-09-501	10/14/99	244.23	245.63	3	2		H	Not pumped for 24 hours prior to measurement
	Kerr	68-09-501	12/27/99	241.42	242.82	Owner	2		H	Not pumped for 18 hours prior to measurement
	Kerr	68-09-501	1/13/00	241.35	242.75	3	2		H	Not pumped for 24 hours prior to measurement

Figures 7 – 27 in the appendix show the 1999 – 2000 water levels at the water level network monitoring well sites scattered throughout the study area (Fig. 1). Some of the sites include information for 1999 only due to malfunction of equipment or unavailability of the data. Figure 22 for Bandera County well 69-14-608 shows that during occasional large rises on the Medina River, the groundwater well mimics streamflow water levels, being only a few miles from the Medina River. Because this site responds to river water changes, it is possible to calculate aquifer parameters using methods proposed by Powers and Shevenell (2000). However, the value of the monitoring well for aquifer analyses is questionable.

The purpose of the water level monitoring network is to obtain spatial and temporal definition of Δh as required for Eq. (1) calculations. In general, all sites show negative Δh values due to low rainfalls for much of 1999-2000 (Table 2). However some sites show small positive Δh values during May-June 2000 and all sites show large positive Δh values during Nov-Dec 2000 that are continuing at several wells into 2001. The changes in Δh values representing average declines or increases in aquifer heads at wells in the study area for 1999-2000 are tabulated in Table 4. This study makes use of positive water level changes only.

Table 4. Δ h Values in feet at network wells, 1999-2000

Well		1999 Δh (+)	1999 Δh(-)	2000 Δh (+)	2000 Δh(-)
Blanco	57-53-305	2	10	10	6
Blanco	57-53-614	15	35	18	35
Comal	68-13-806	5	50	56	6
Comal	68-06-709	1	4	5	2
Comal	69-14-407	0	62	69	2
Gillespie	56-47-908	3	2	2	2
Gillespie	56-56-602	1	2	1	1
Gillespie	57-42-722	3	7	12	13
Gillespie	57-41-403	1	2	1	2
Hays	57-45-401	2	44	20	24
Hays	57-56-710	1	27	46	15
Hays	57-64-705	9	52	49	41
Hays	57-63-703	0	3	2	1
Kendall	68-02-609	10	40	49	20
Kendall	68-01-314	6	33	20	13
Kendall	68-11-417	6	57	47	24
Kendall	68-11-715	2	23	17	7
Kendall	57-58-706	1	12	9	15
Bandera	69-14-608	1	2	3	1
Kerr	56-62-408	4	17	NA	NA
Kerr	56-63-916	36	54	NA	NA
Kerr	57-57-703	25	30	NA	NA
Kerr	68-09-501	3	11	NA	NA

NA --- Not available for Kerr County for 2000

Because a rise in water level on any graph can be due to a combination of recharge, seasonal reduction in pumpage and evapotranspiration, and general effects of pumpage prior to and during recharge events, an adjustment has to be made in the positive Δh values. The effect of pumping during recharge was accounted for by interpolating Δh declines during active recharge periods. Because seasonal recovery of water levels usually occurs during Fall –Winter periods, separation of this effect from recharge had to be estimated. In general, recharge from significant rainfall events was assumed to cease from the given event within 2-4 weeks after the recorded local rainfalls ceased. In general, recharge events occur as a result of a series of closely spaced daily rainfalls large enough to cause vertical movement of recharging precipitation, after runoff and evapotranspiration have been abstracted.

Analysis and Results

The Δh values shown in Table 4 were plotted on a map of the study region to see if a pattern exists for 1999 and 2000 recorded values. No pattern appears to exist except that significantly larger water-level changes, associated with recharge, occur in areas of heavy pumping near cities. This might imply that recharge in some parts of the study region is related to available storage caused by pumping. Mace (2001) concludes that reduction of pumping after rainfalls in such areas allows pre-existing waters to fill the depression. Finding no pattern, average values were used as follows: $\Delta h = 6$ ft. for 1999; $\Delta h = 23$ ft. for 2000.

If Eq. (1) is applied using the data summarized above, the following recharge results are obtained for the Middle Trinity Aquifer:

Calendar Year, 1999

Average $\Delta h = 6$ feet; $S_y = 8 \times 10^{-4}$; Recharge = 13,800 acre-feet
Mace and others (2000), Table 12; Drought Recharge = 26,600 acre-feet

Calendar Year, 2000

Average Δh=23 feet; S_y=8 x 10^{-4}; Recharge = 53,000 acre-feet
Mace and others (2000), Table 12; Normal Recharge = 364,800 acre-feet

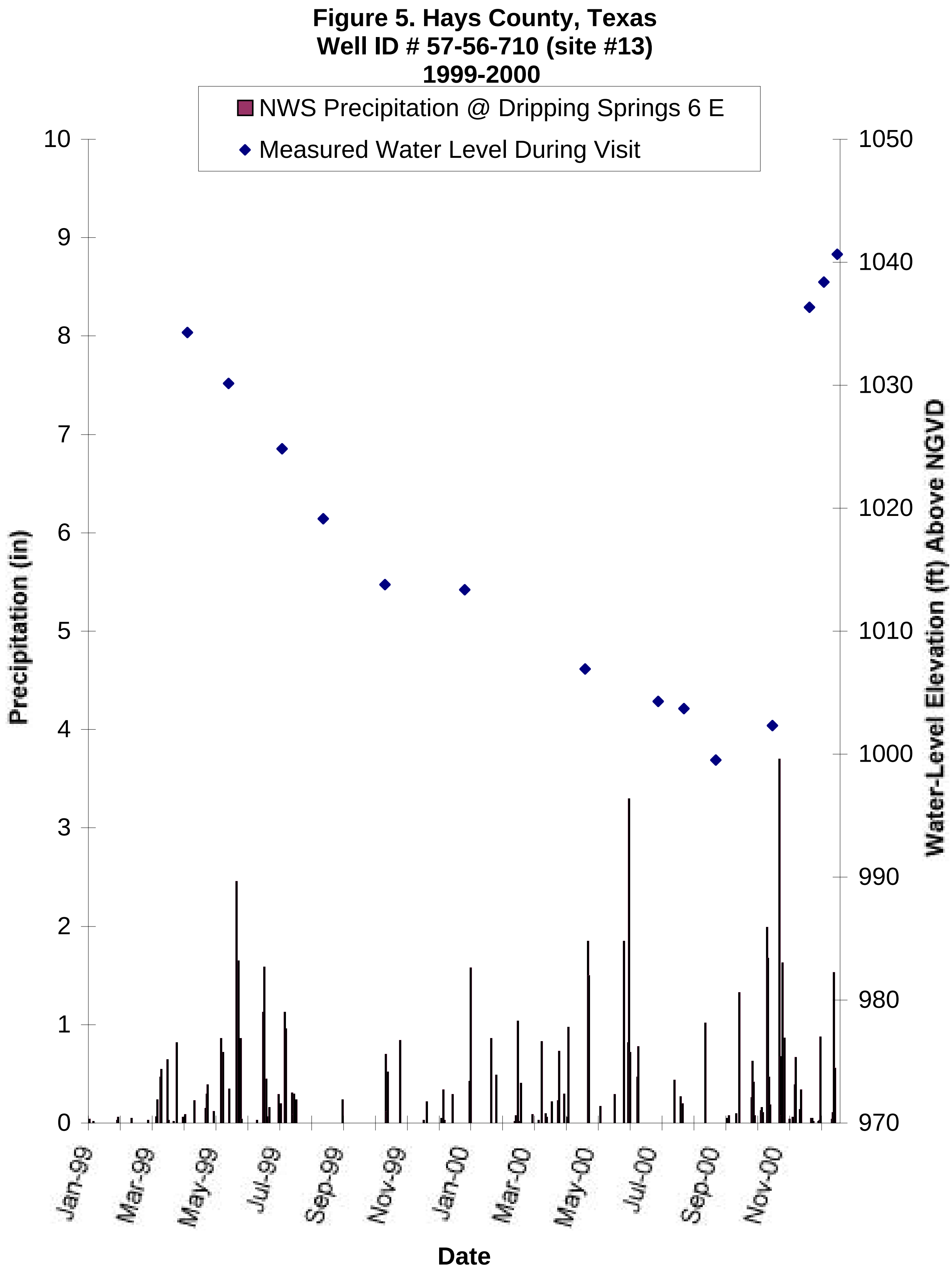


Figure 5. Hays County, Texas
Well ID # 57-56-710 (site #13)
1999-2000
NWS Precipitation @ Dripping Springs 6 E
Measured Water Level During Visit
Precipitation (in)
Water-Level Elevation (ft) Above NGVD
Date
0
1
2
3
4
5
6
7
8
9
10
970
980
990
1000
1010
1020
1030
1040
1050
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00

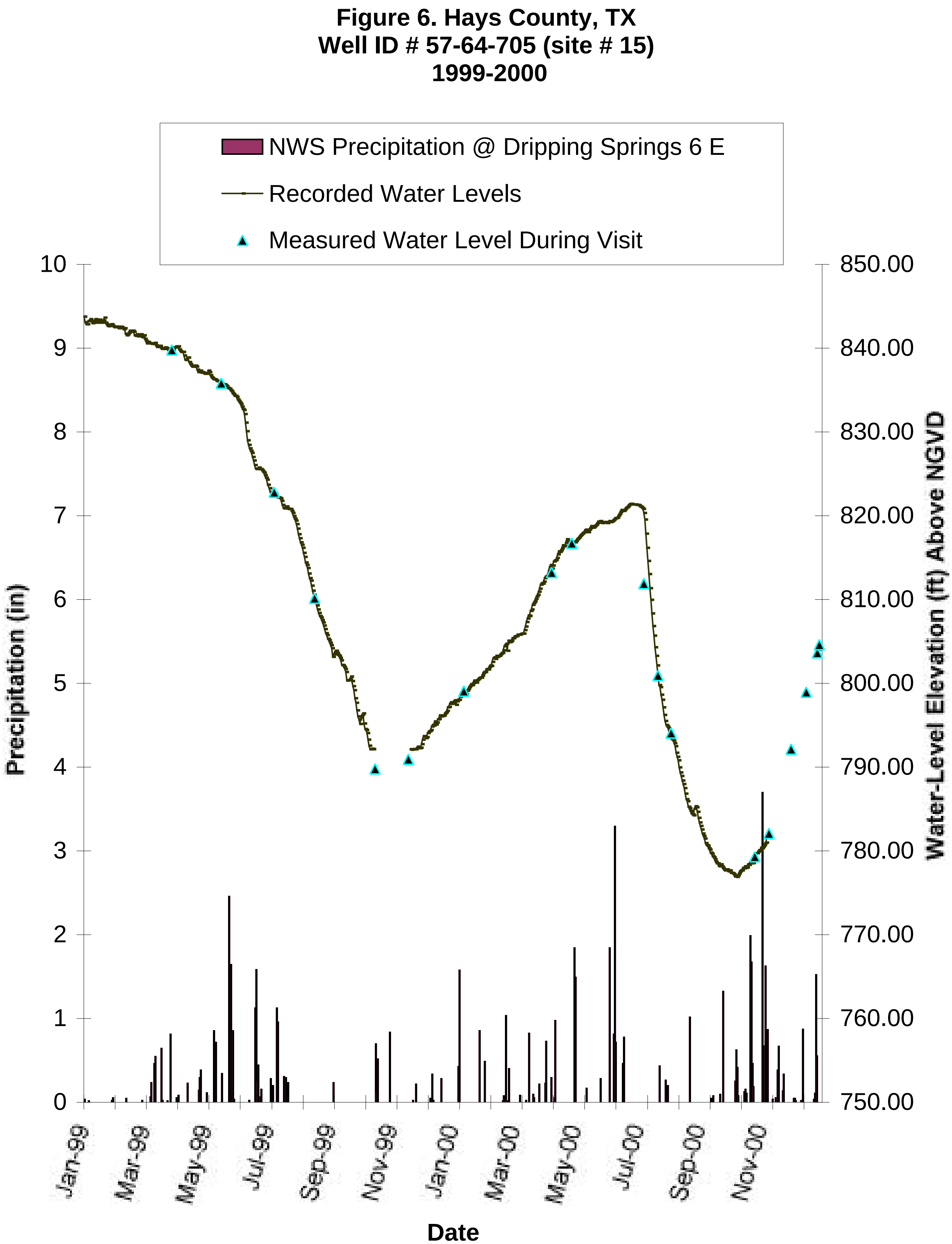


Figure 6. Hays County, TX
Well ID # 57-64-705 (site # 15)
1999-2000
NWS Precipitation @ Dripping Springs 6 E
Recorded Water Levels
Measured Water Level During Visit
Precipitation (in)
Water-Level Elevation (ft) Above NGVD
Date
0
1
2
3
4
5
6
7
8
9
10
750.00
760.00
770.00
780.00
790.00
800.00
810.00
820.00
830.00
840.00
850.00
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00

According to calibrated, steady-state numerical model results obtained by Mace and others (2000) using information from 1975, about 131,000 (AF) was calculated to recharge the Middle Trinity Aquifer. The results in this report are substantially less than this value and are less than 15% of recharge calculated using 4% of annual rainfall. The reasons for this include the fact that substantially lower annual rainfalls were experienced throughout the study area during 1999 and through much of 2000. Thus, lower than average annual recharge could be expected. Other reasons for the disparity include a limited network of monitoring well sites, an inadequate definition of aquifer storativity values, and uncertainty concerning confined versus unconfined conditions. Further, some of the wells were located too close to rivers and creeks to be representative of general aquifer conditions, or were in parts of the study region where the Middle Trinity Aquifer is only marginally present.

Some of these issues are being resolved. The HCA is promoting expansion of the monitoring well network to include additional recording well sites and perhaps additional non-recording well sites. HCA has contracted with the EARDC to continue operation of about 30-35 well monitoring sites, including 8 recording sites. HCA also plans to compile new aquifer storativity values now being collected by local county governments as part of S. B. 1 water availability ordinances.

Conclusions

This report has obtained data from a well monitoring network of 23 sites in the Middle Trinity Aquifer, scattered throughout the Texas Hill Country. The water-level information is believed to be representative of regional levels but does show considerable variation in time and space as would be expected of karst aquifer systems. Recording sites and rainfall were used to shape water levels at all sites for 1999 and 2000. Using aquifer storativity and specific yield values obtained from Mace and others (2000), calculations of annual recharge to the aquifer were made for 1999 and 2000. The calculations yielded recharge values of about 14,000 AF and 53,000 AF for 1999 and 2000 respectively. These values are substantially less than recharge values calculated using the stream baseflow method, augmented by numerical model results, Mace and others (2000). To bring the recharge results by the two methods into a comparable range, a larger value of aquifer storativity in the range of 10^{-3} to 10^{-2} was arbitrarily selected. Such values are not unreasonable for limestone aquifers and might be validated if storativity or specific yield values could be determined at the wells used in this study. Given the uncertainty of aquifer parameters in karst aquifer systems, more determinations and study of the meaning of 2-well aquifer tests as applied to large regions may be warranted. Refinement of storativity information and an enhanced well monitoring network with nine additional TWDB recorders may decrease the disparity between recharge values based on stream baseflow and modeling, versus the method suggested in this report. With improved results, the two methods could also be used conjunctively.

References Cited

Ashworth, J.B., 1983, Ground-water availability of the Lower Cretaceous Formations in the Hill Country of south-central Texas: Texas Department Of Water Resources Report 273, 173 pp.

Barnes, B.S., 1939, The structure of discharge recession curves: Trans. Am. Geophys. Union, Vol 20, p. 721-725.

Bluntzer, R.L., 1992, Evaluation of Ground-water Resources of the Paleozoic And Cretaceous Aquifers in the Hill Country of Central Texas: Texas Water Development Board Report 339, 130 pp.

Fetter, C.W., 1994, Applied Hydrogeology, Third Edition: Prentice Hall, 691p.

Halford, K.J., Mayer, G.C., 2000, Problems Associated with Estimating Ground Water Discharge and Recharge from Stream-Discharge Records: Ground Water, Vol. 38, No. 3, pp. 331-342.

Kuniansky, E.L., 1989, Precipitation, streamflow, and baseflow, in west-central Texas, December 1974 through March 1977: U.S. Geological Survey, Water Resources Investigations Report 89-4208, 2 sheets.

Kuniansky, E.L., and Holligan, K.Q., 1994, Simulations of flow in the Edwards-Trinity aquifer system and contiguous hydraulically connected Units, west-central Texas: U.S. Geological Survey Water-Resources Investigations Report 93-4039, 40 pp.

LBG-Guyton Associates, 2001, Hydrologic Evaluation And Modeling of Well Field Located on Oliver Ranch in Northern Bexar County, Texas, Prepared For San Antonio Water System, San Antonio, Texas, 23 p. + figures and Appendicies.

Mace, R.E., Chowdhury, A.H., Anaya, R., and Way, S.-C., 2000, Groundwater Availability of the Trinity Aquifer, Hill Country Area, Texas: Numerical Simulations through 2050, Final Report: Texas Water Development Board, 169 p.

Mace, R.E., Mullican, W.F., and Way, S.-C., 2001, Estimating Groundwater Availability in Texas, in Proc, First Annual Texas Rural Water Association and Texas Water Conservation Association Water Law Seminar: " Water Allocation in Texas: The Legal Issues," Austin, TX, January 25-26, 2001, 16 p.

Mace, R.E., 2001, Personal Communication

McDonald, M.G. and Harbaugh, A.W., 1988, A modular three-dimensional Finite-difference ground-water flow model (MODFLOW): U.S. Geological Survey Techniques of Water-Resources Investigations, Book, 100 p.

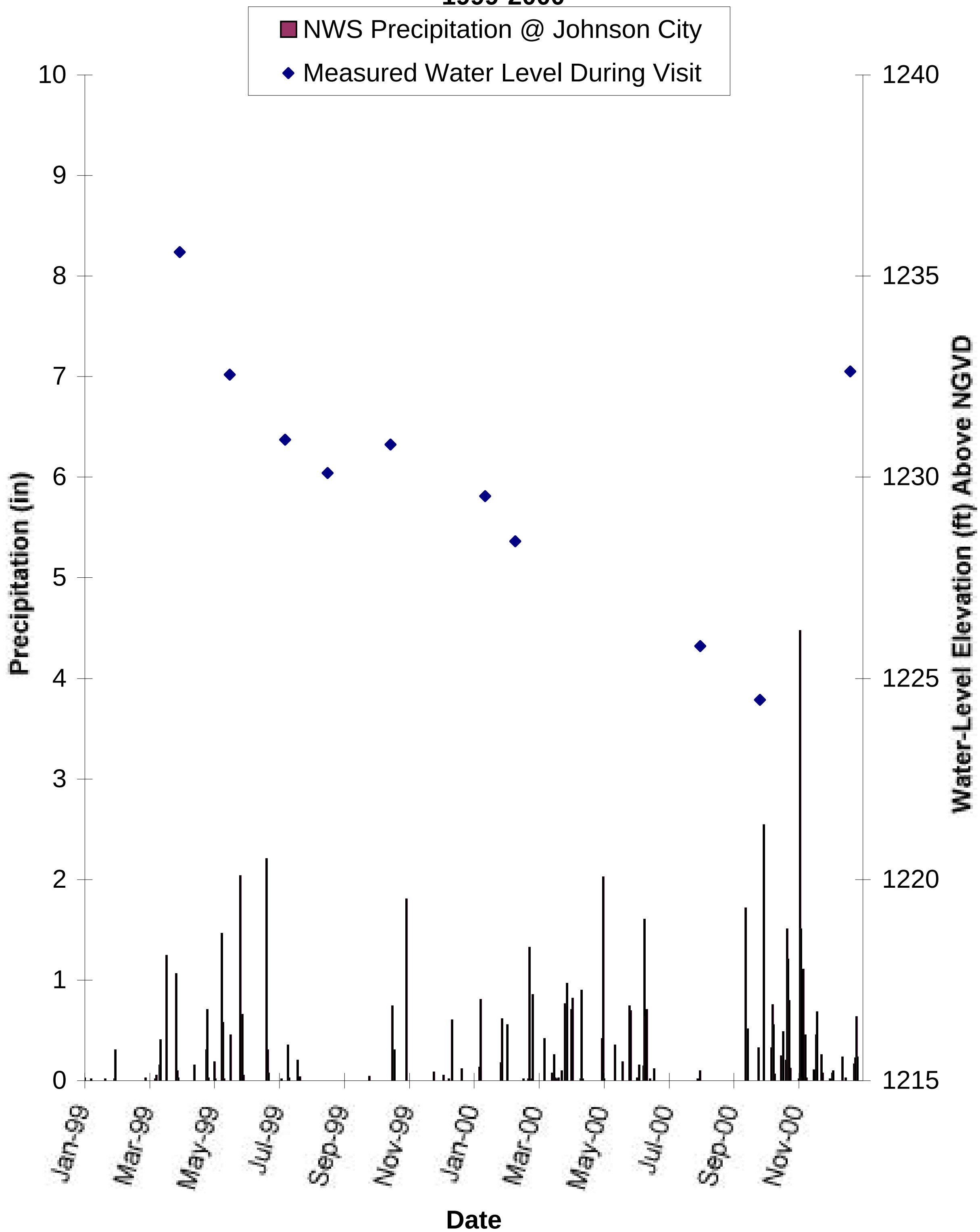
Muller, D.A., and Price, R.D., 1979, Ground-water Availability in Texas, Estimates and Projections Through 2030: Texas Department of Water Resources Report 238, 77 p.

Pool, D.R., Eychaner, J.H., 1995, Measurements of Aquifer-Storage Change And Specific Yield Using Gravity Surveys: Ground Water, Vol. 33, No. 3 pp. 425-432.

Powers, J.G., and Shevenell, L., 2000, Transmissivity Estimates from Well Hydrographs in Karst and Fractured Aquifers: Ground Water, Vol. 38, No. 3, pp. 361-369.

Appendix

Figure 7. Blanco County, TX
Well ID # 57-53-305 (site # 2)
1999-2000



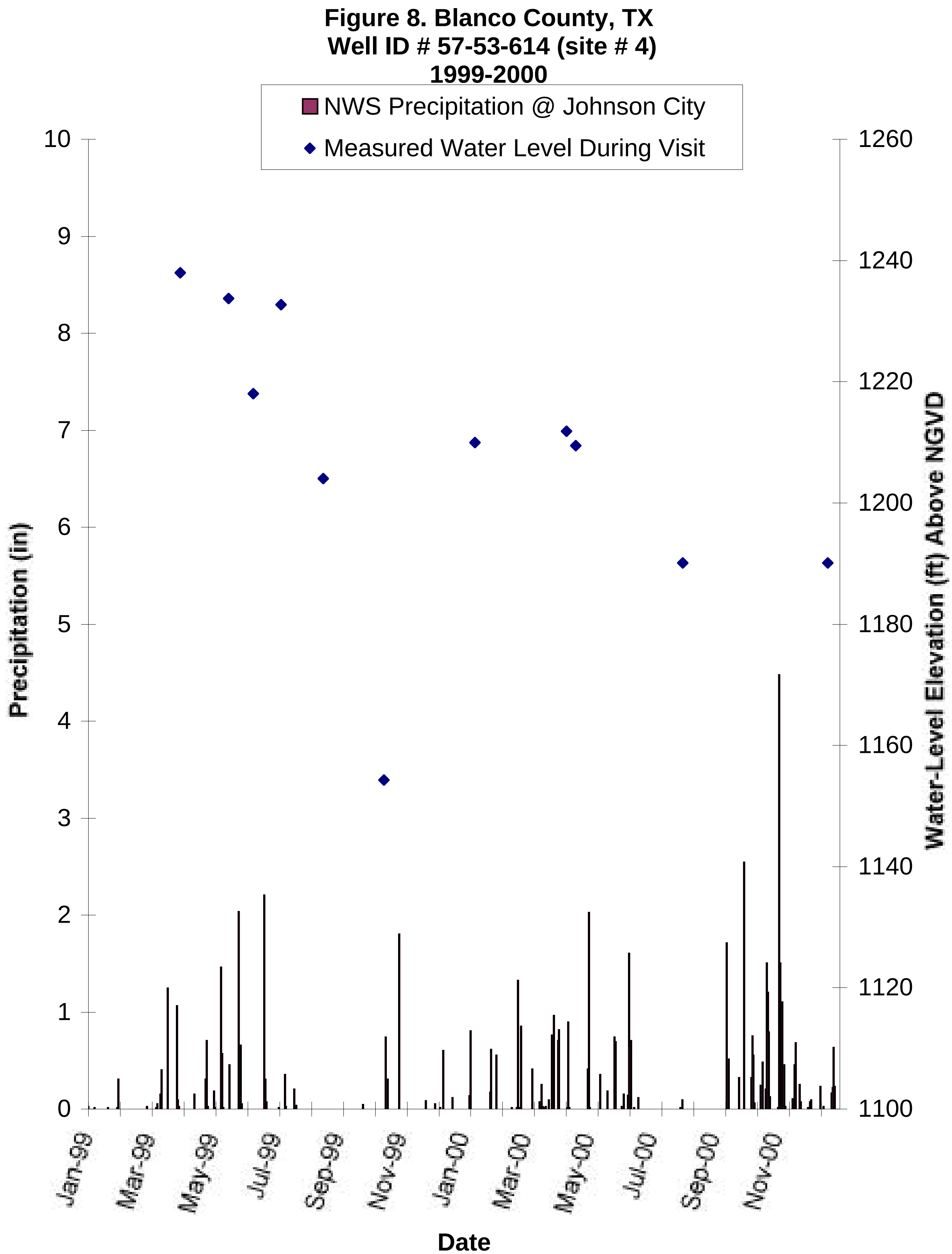


Figure 8. Blanco County, TX
Well ID # 57-53-614 (site # 4)
1999-2000
NWS Precipitation @ Johnson City
Measured Water Level During Visit
Precipitation (in)
Water-Level Elevation (ft) Above NGVD
Date
0
1
2
3
4
5
6
7
8
9
10
1100
1120
1140
1160
1180
1200
1220
1240
1260
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00

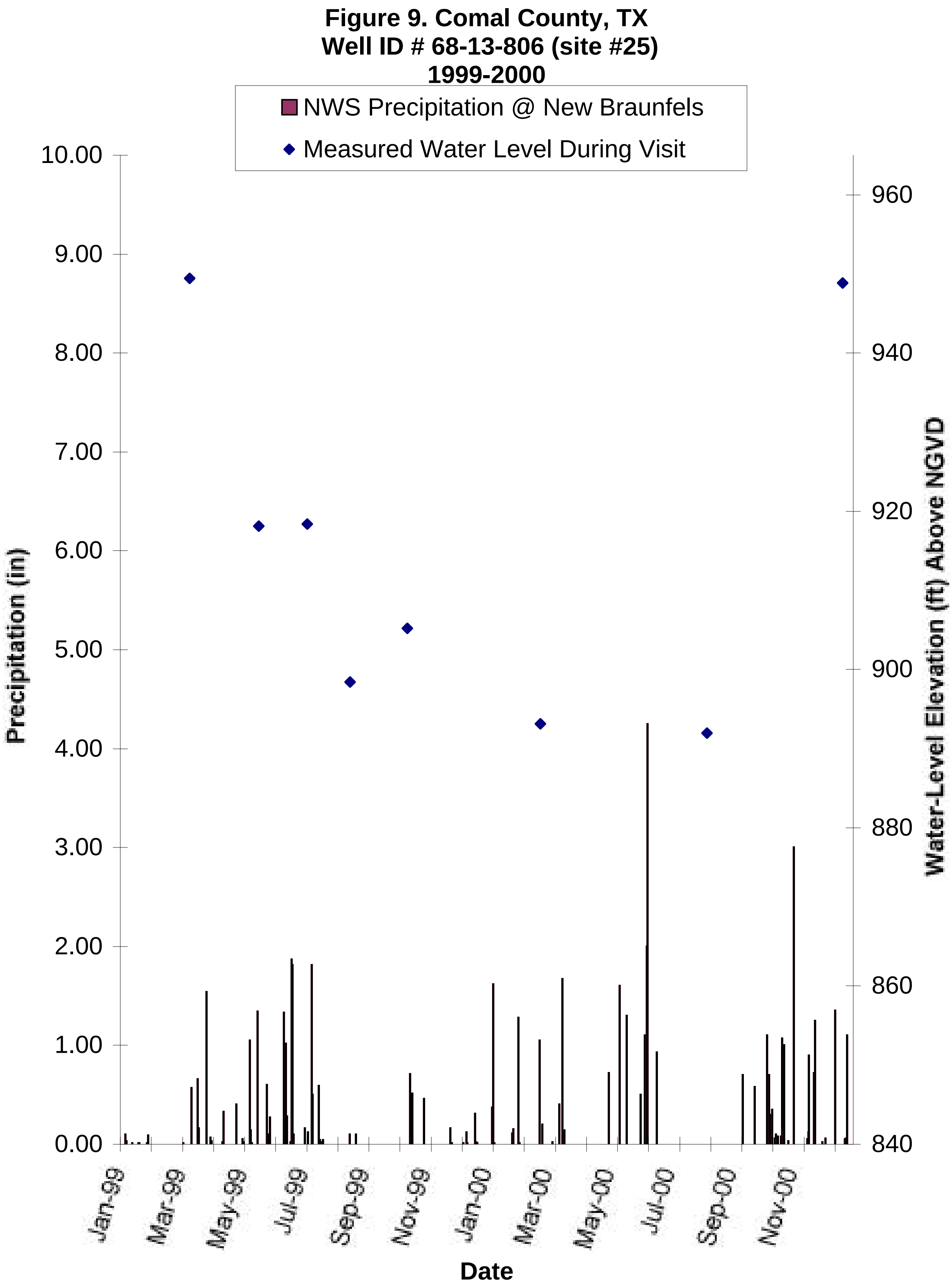


Figure 9. Comal County, TX
Well ID # 68-13-806 (site #25)
1999-2000
NWS Precipitation @ New Braunfels
Measured Water Level During Visit
Precipitation (in)
Water-Level Elevation (ft) Above NGVD
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
960
940
920
900
880
860
840
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Date

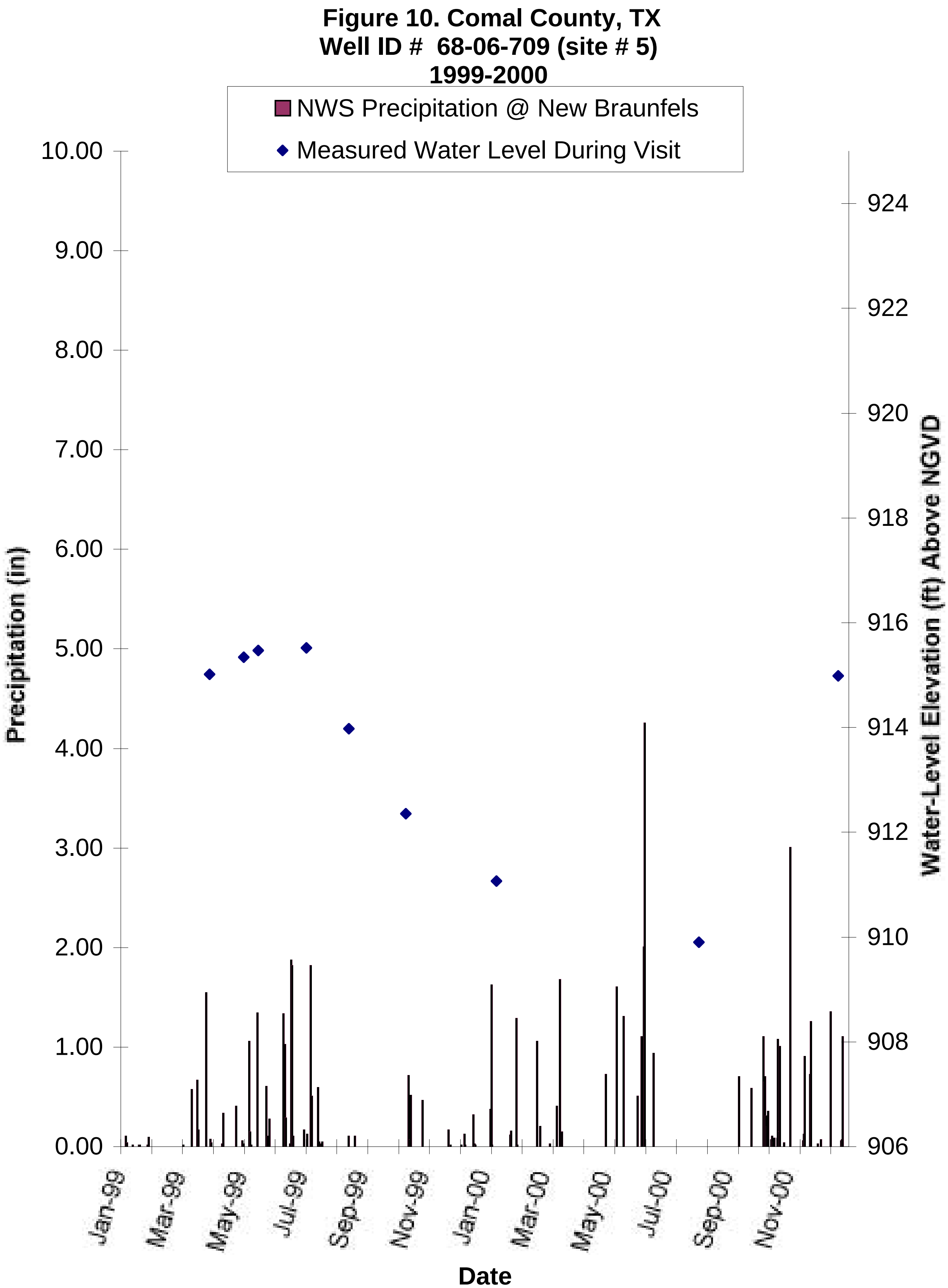


Figure 10. Comal County, TX
Well ID # 68-06-709 (site # 5)
1999-2000
NWS Precipitation @ New Braunfels
Measured Water Level During Visit
Precipitation (in)
Water-Level Elevation (ft) Above NGVD
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
924
922
920
918
916
914
912
910
908
906
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Date

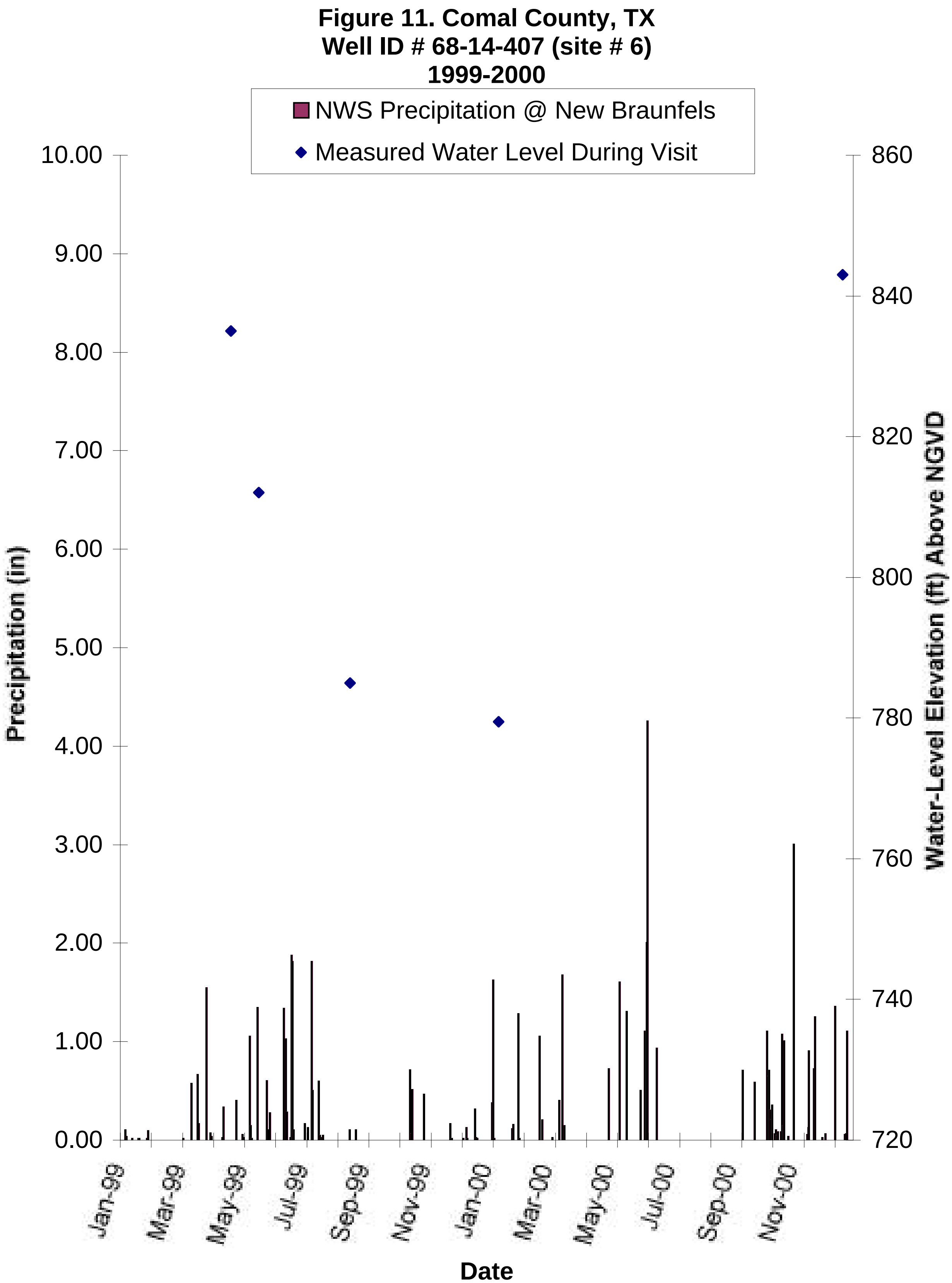
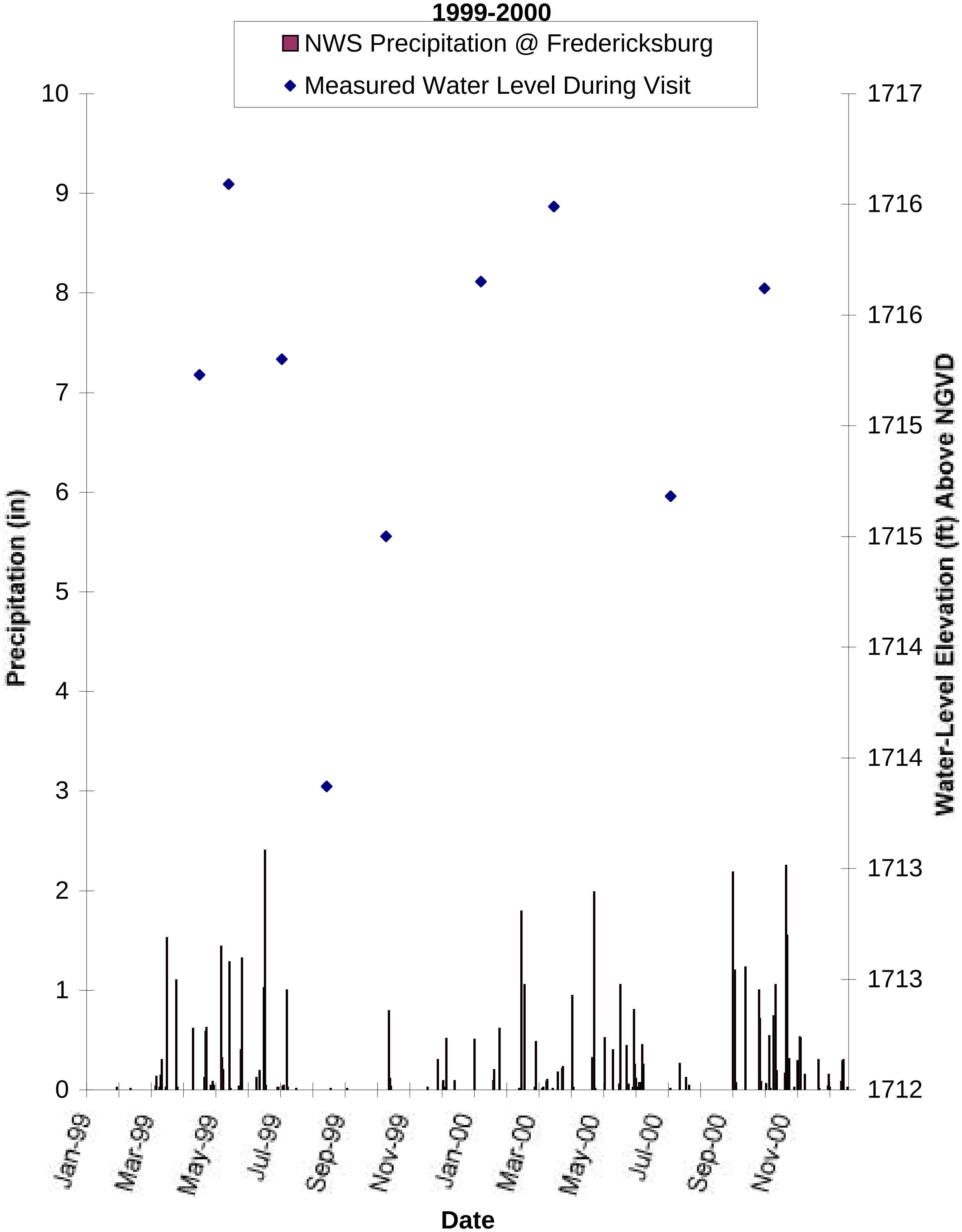


Figure 11. Comal County, TX
Well ID # 68-14-407 (site # 6)
1999-2000
NWS Precipitation @ New Braunfels
Measured Water Level During Visit
Precipitation (in)
Water-Level Elevation (ft) Above NGVD
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
860
840
820
800
780
760
740
720
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Date

Figure 12. Gillespie County , TX
Well ID # 56-47-908 (site # 7)
1999-2000



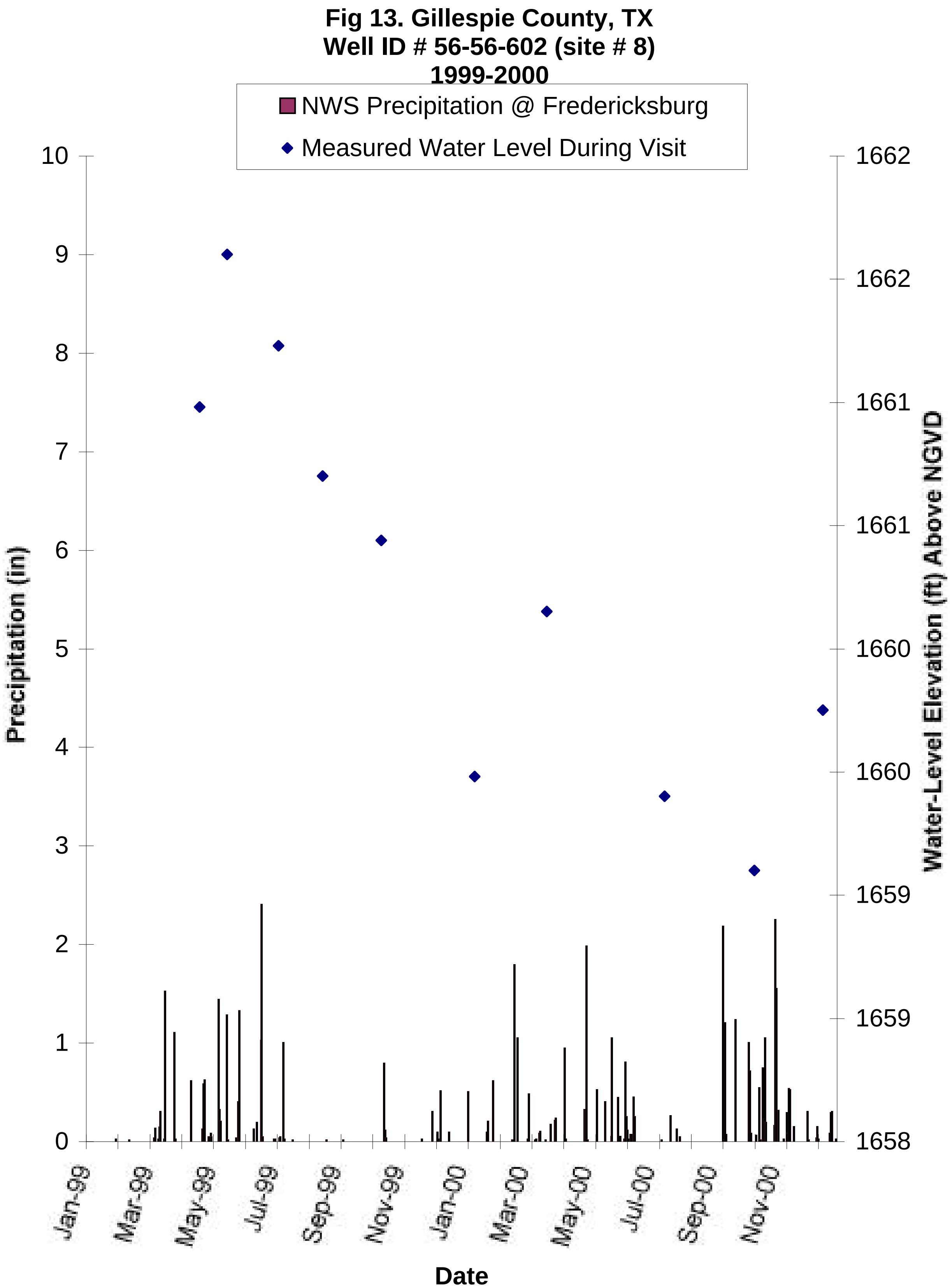


Fig 13. Gillespie County, TX
Well ID # 56-56-602 (site # 8)
1999-2000
NWS Precipitation @ Fredericksburg
Measured Water Level During Visit
Precipitation (in)
Water-Level Elevation (ft) Above NGVD
10
9
8
7
6
5
4
3
2
1
0
1662
1662
1661
1661
1660
1660
1659
1659
1658
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Date

Figure 14. Gillespie County, TX
Well ID # 57-42-722 (site # 10)
1999-2000

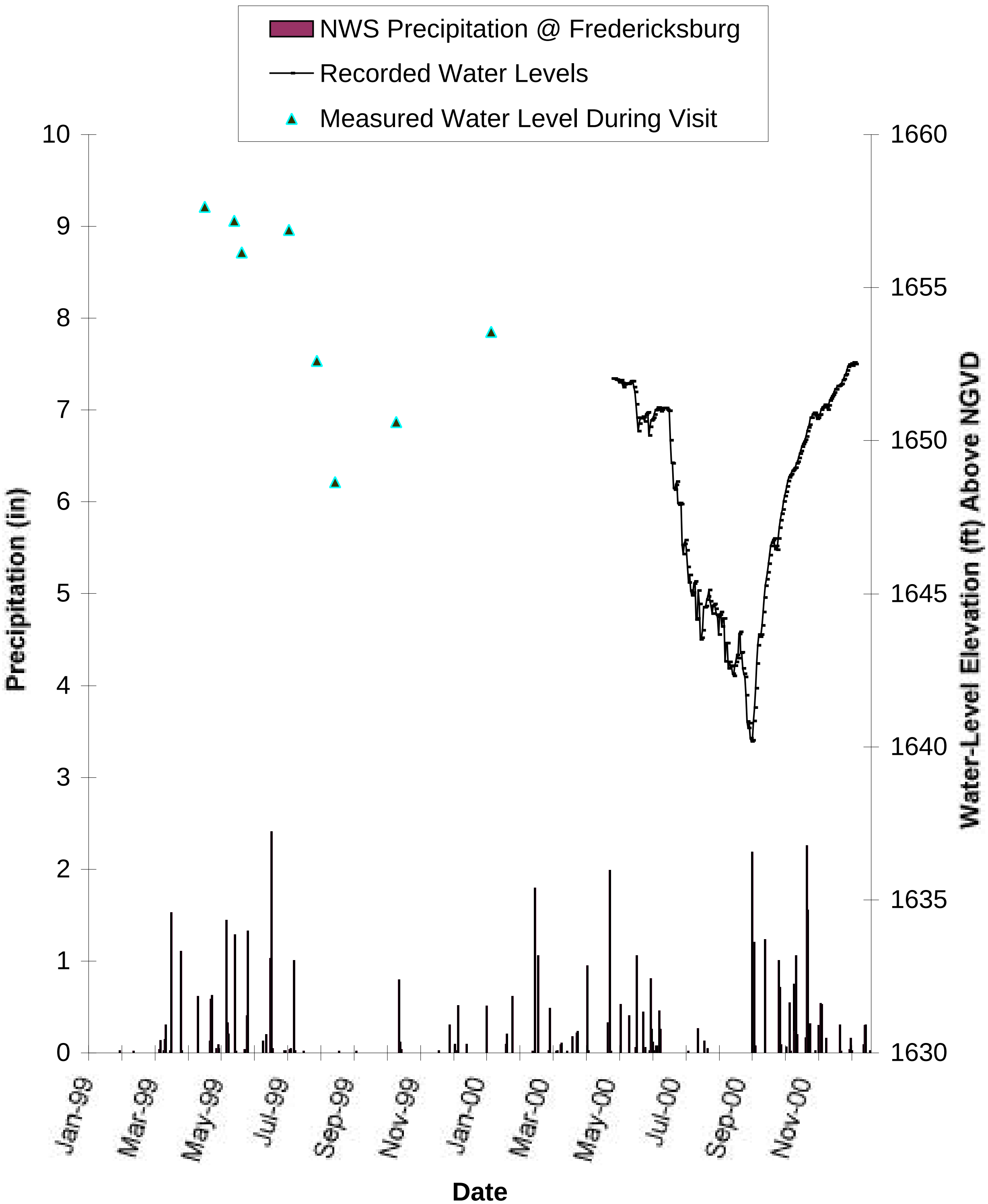


Figure 15. Gillespie County, TX
Well ID # 57-41-403 (site # 9)
1999-2000

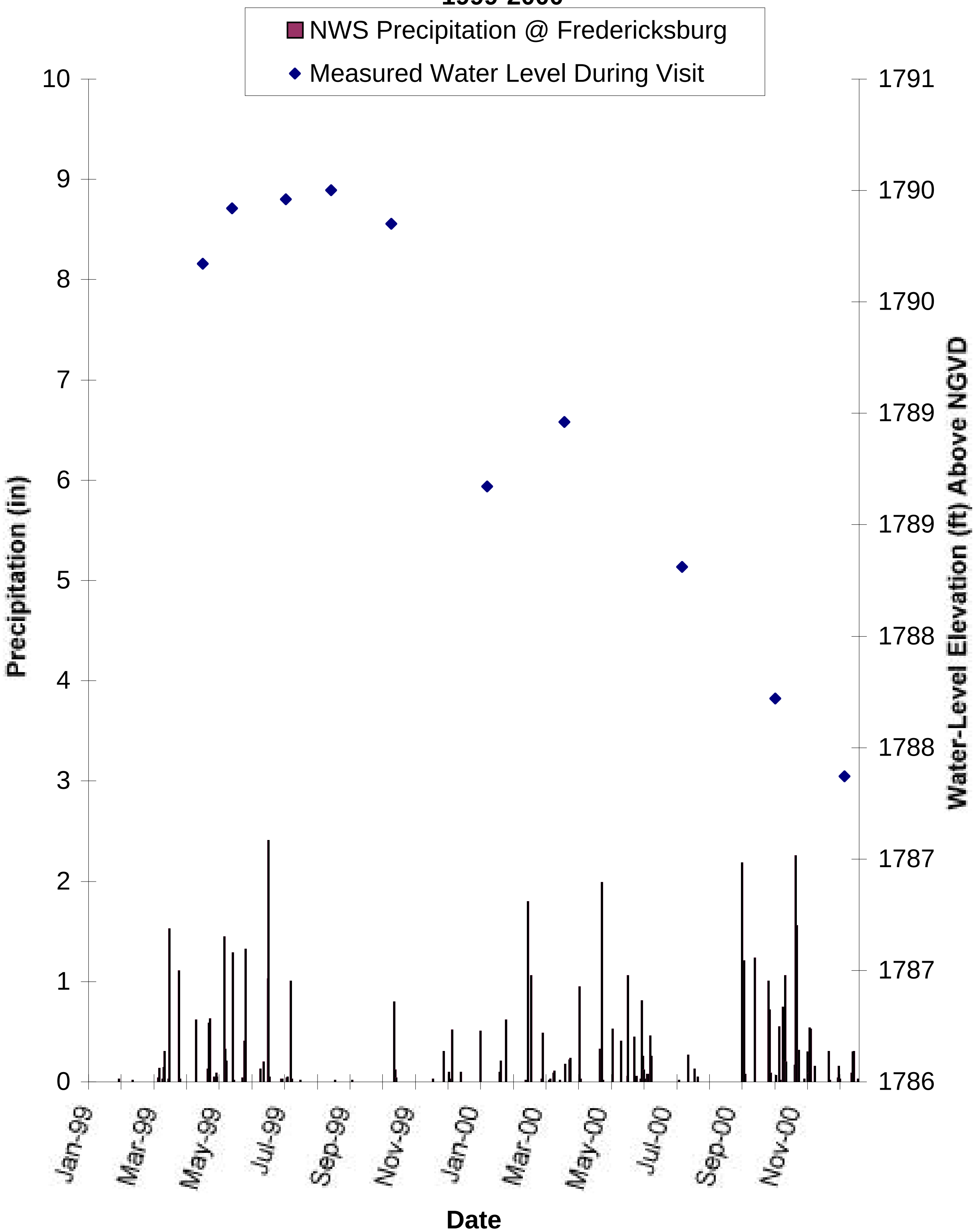


Figure 16. Hays County, TX
Well ID # 57-55-401 (site # 12)
1999-2000

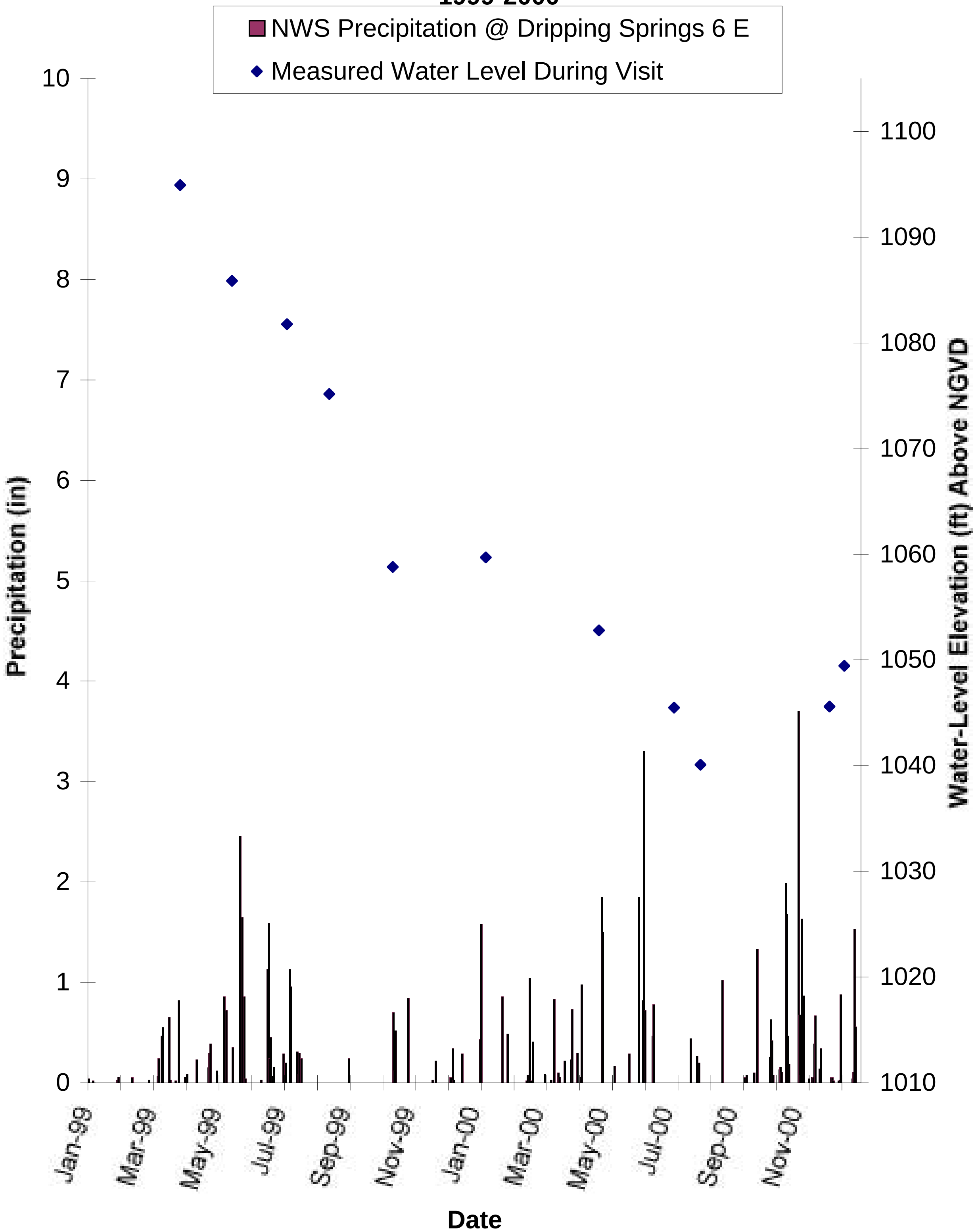


Figure 17. Hays County, TX
Well ID # 57-63-703 (site # 14)
1999-2000

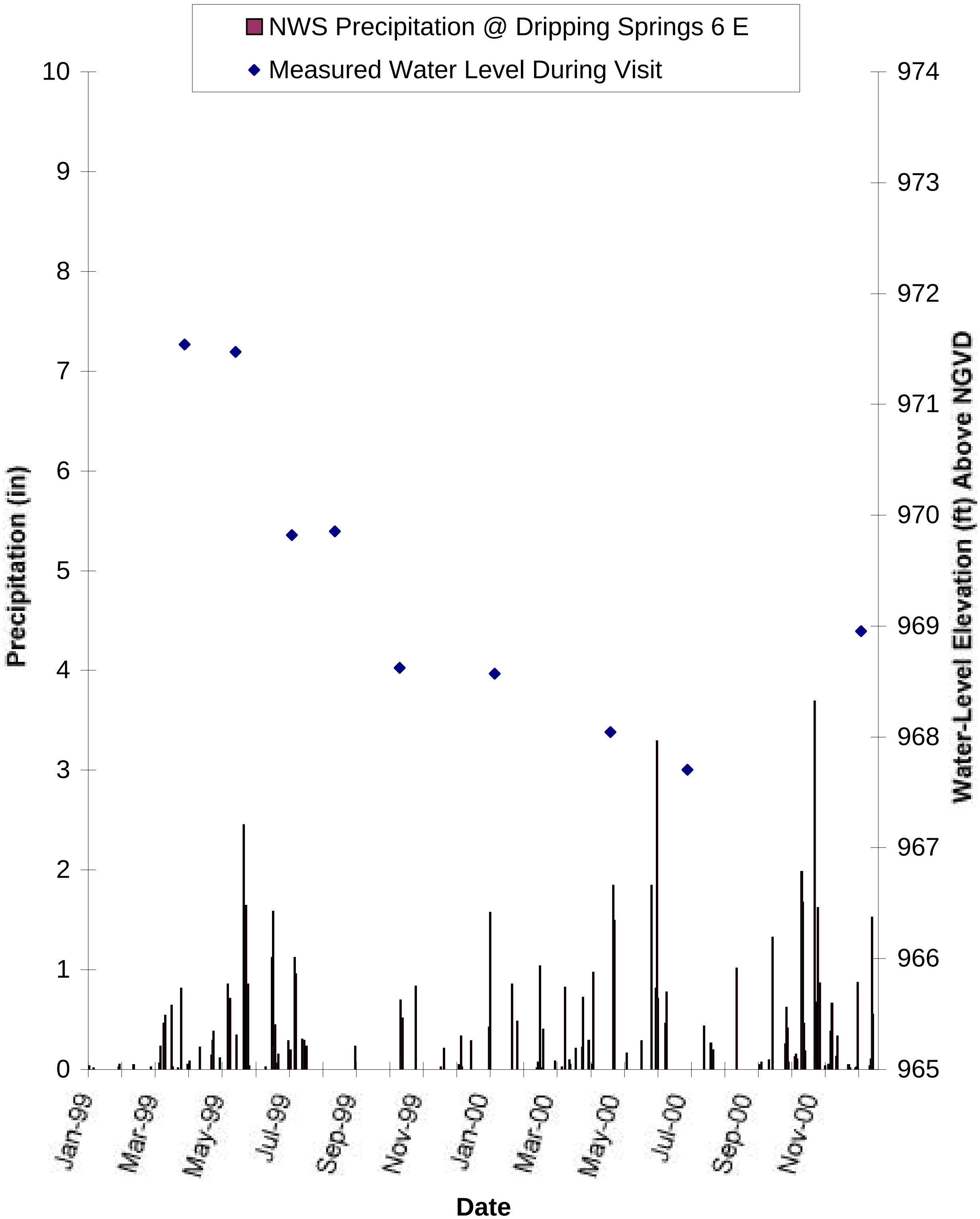


Figure 18. Kendall County, TX (operated by TWDB)
Well ID # 57-41-609 (site # 18)
1999-2000

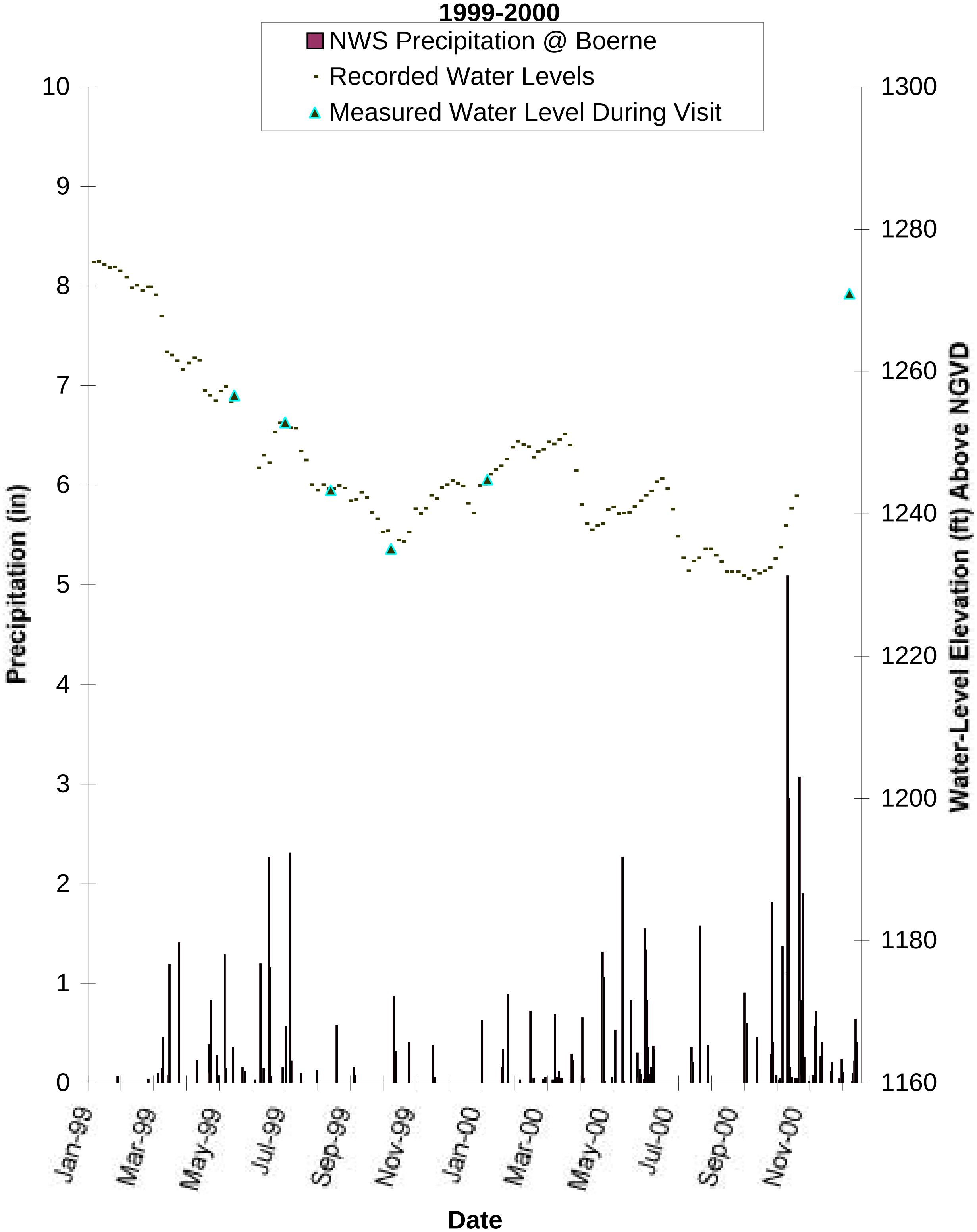
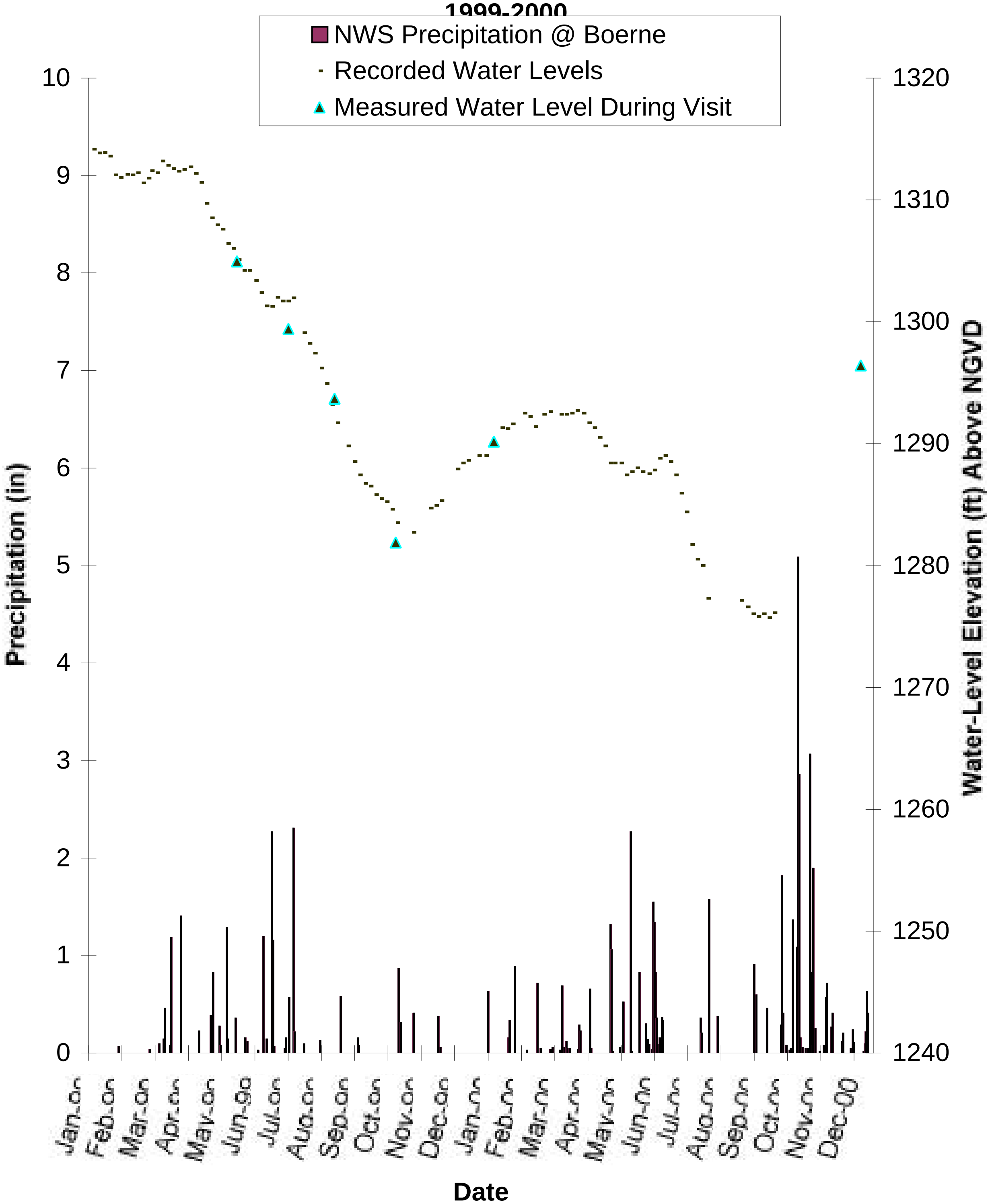


Figure 19. Kendall County, TX (formerly operated by TWDB, presently by USGS)
Well ID # 68-01-314 (site # 17)
1999-2000



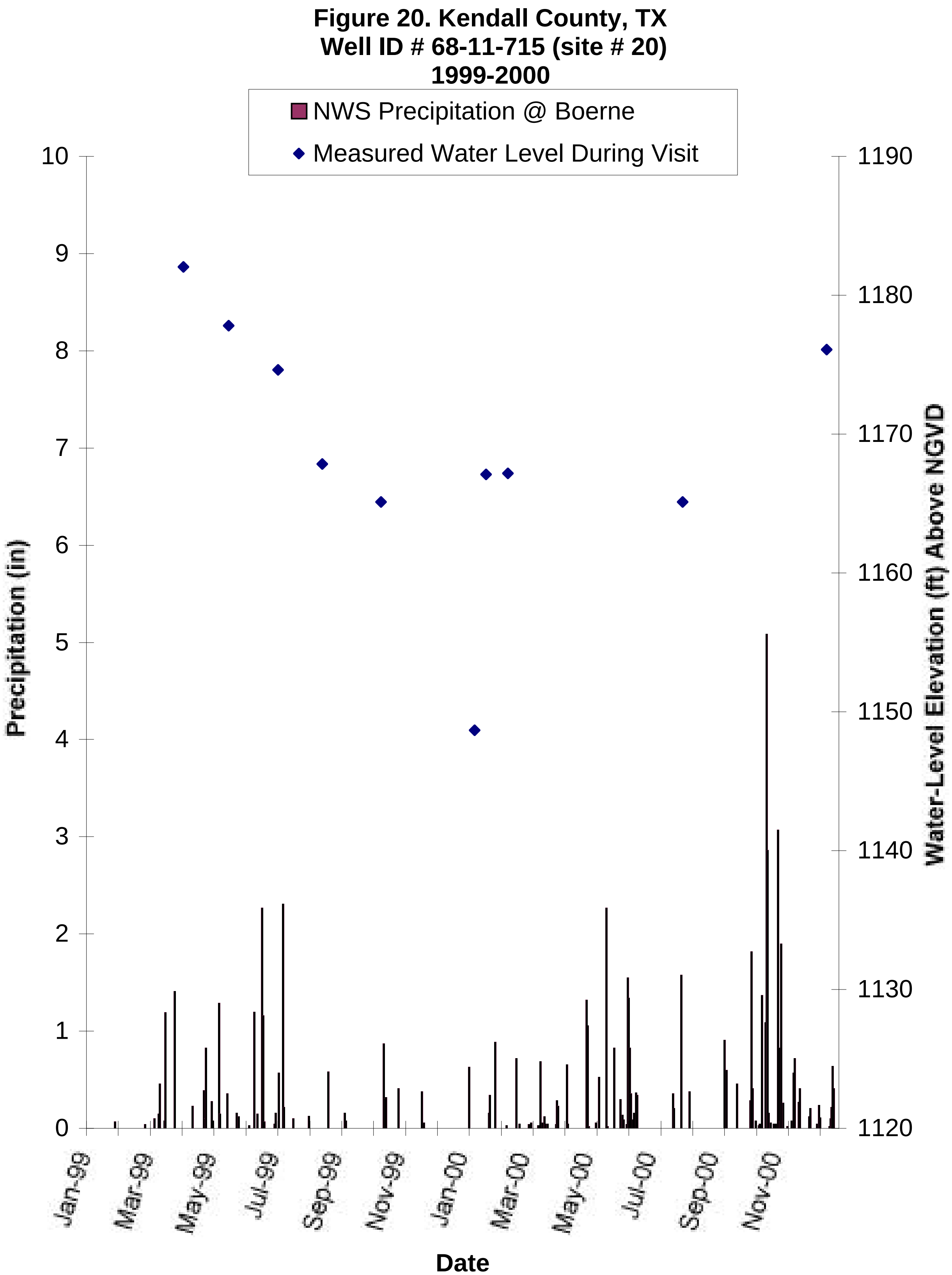


Figure 20. Kendall County, TX
Well ID # 68-11-715 (site # 20)
1999-2000
NWS Precipitation @ Boerne
Measured Water Level During Visit
Precipitation (in)
Water-Level Elevation (ft) Above NGVD
Date
0
1
2
3
4
5
6
7
8
9
10
1120
1130
1140
1150
1160
1170
1180
1190
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00

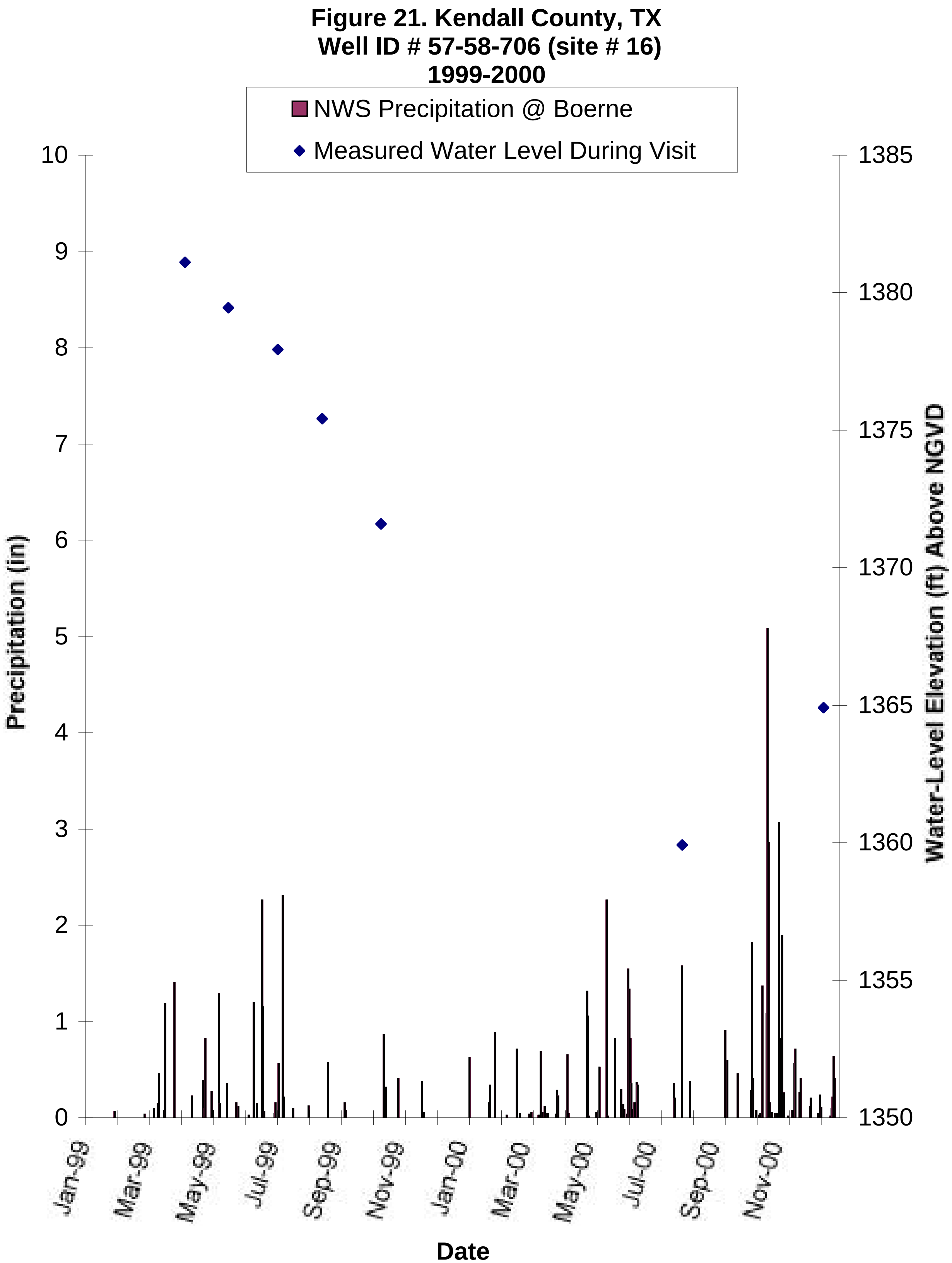
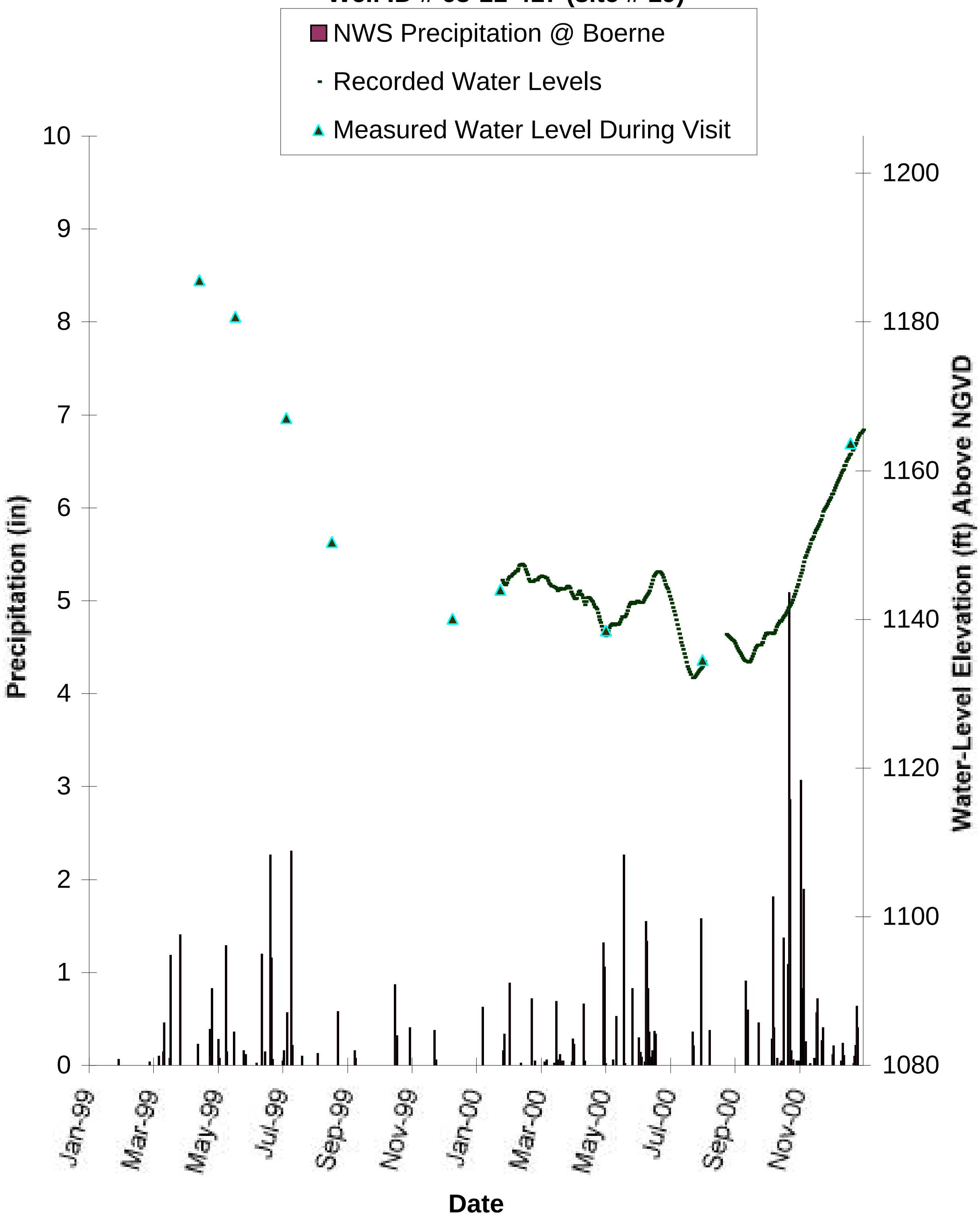


Figure 21. Kendall County, TX
Well ID # 57-58-706 (site # 16)
1999-2000
NWS Precipitation @ Boerne
Measured Water Level During Visit
Precipitation (in)
Water-Level Elevation (ft) Above NGVD
Date
0
1
2
3
4
5
6
7
8
9
10
1350
1355
1360
1365
1370
1375
1380
1385
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00

Figure 22. Kendall County, TX
Well ID # 68-11-417 (site # 19)



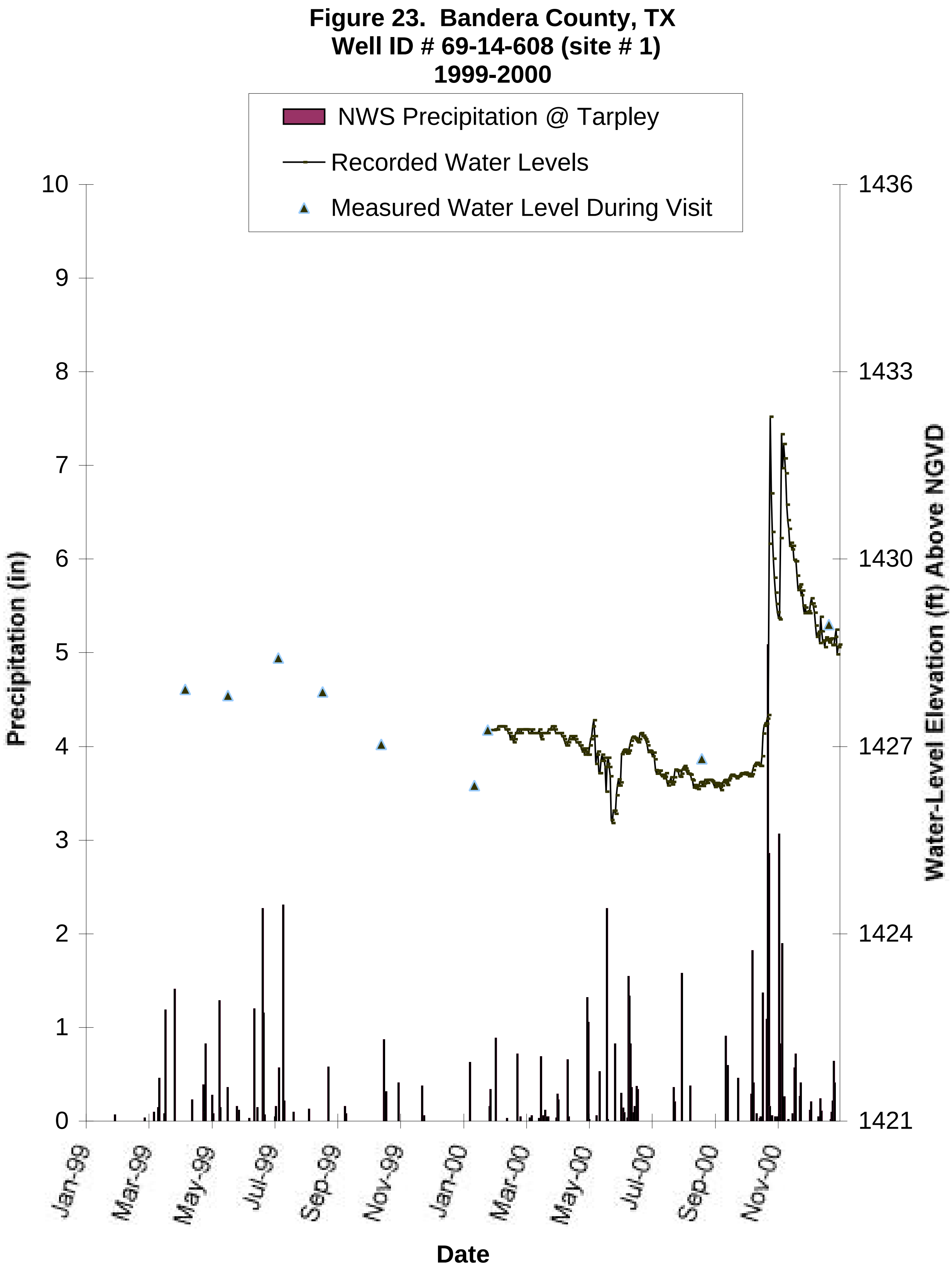


Figure 23. Bandera County, TX
Well ID # 69-14-608 (site # 1)
1999-2000
NWS Precipitation @ Tarpley
Recorded Water Levels
Measured Water Level During Visit
Precipitation (in)
Water-Level Elevation (ft) Above NGVD
Date
10
9
8
7
6
5
4
3
2
1
0
1436
1433
1430
1427
1424
1421
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00

Figure 24. Kerr County, TX
Well ID # 56-62-408 (site # 21)
1999-2000

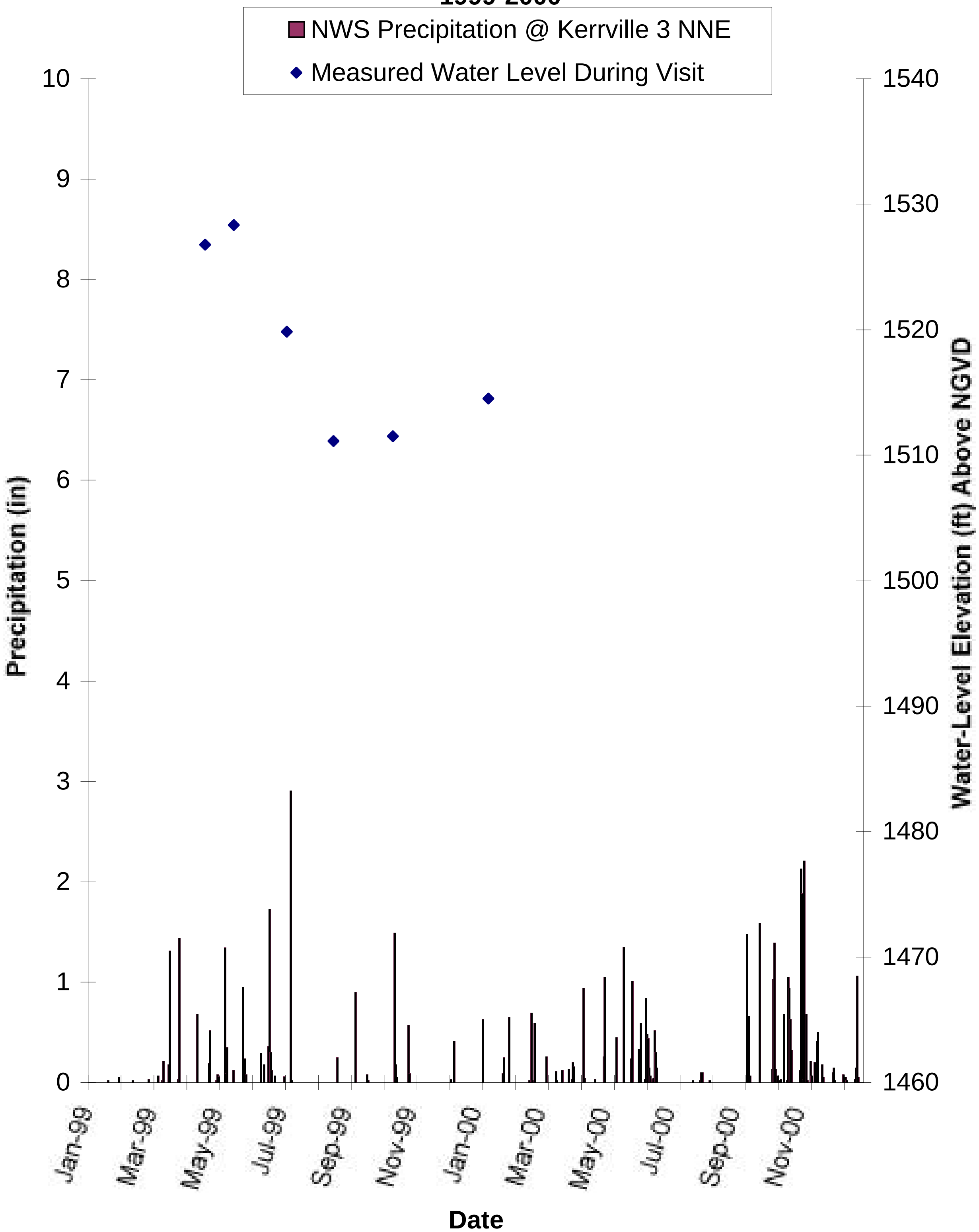


Figure 25. Kerr County, TX
Well ID # 56-63-916 (site # 22)
1999-2000

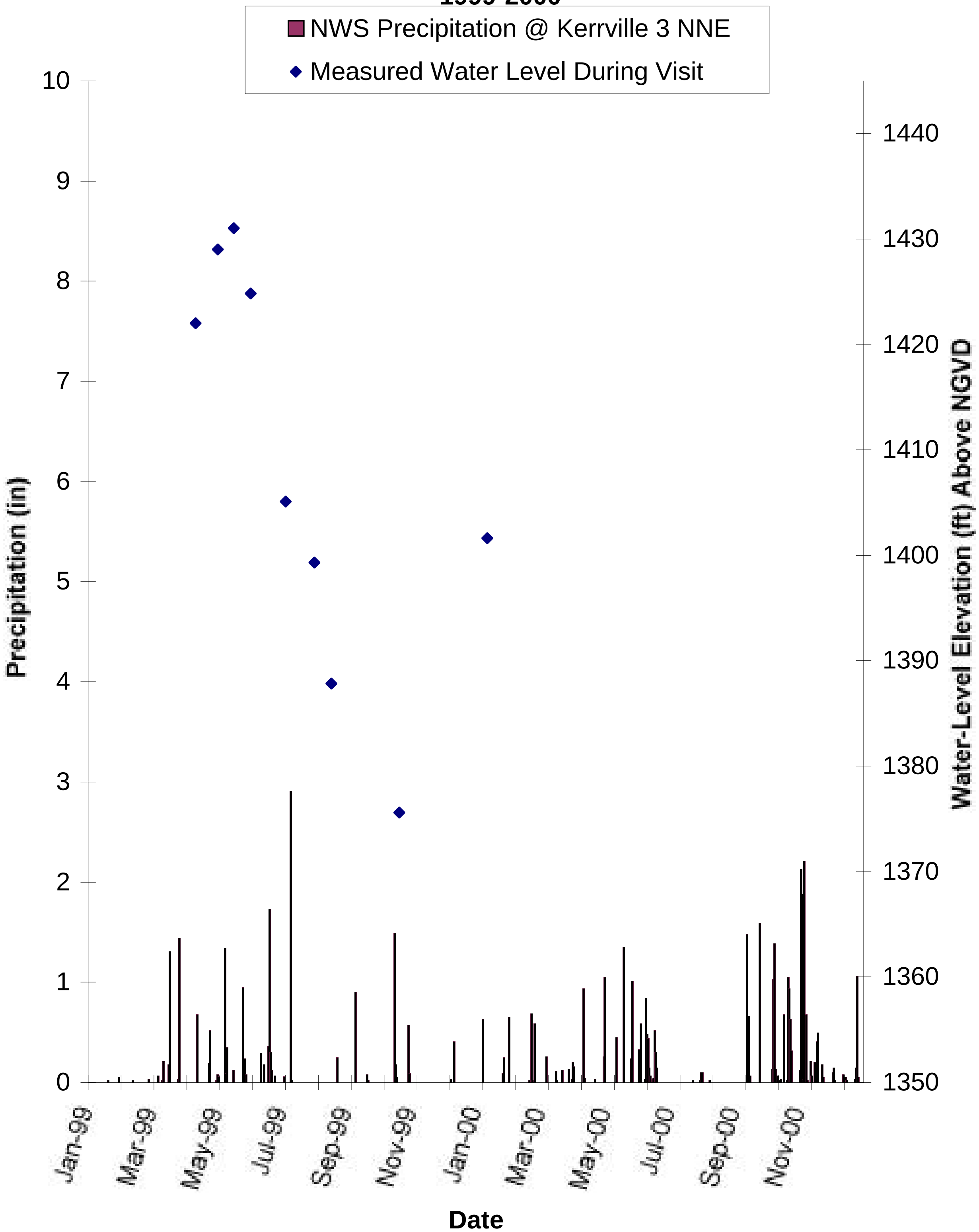


Figure 26. Kerr County, TX
Well ID # 57-57-703 (site # 23)
1999-2000

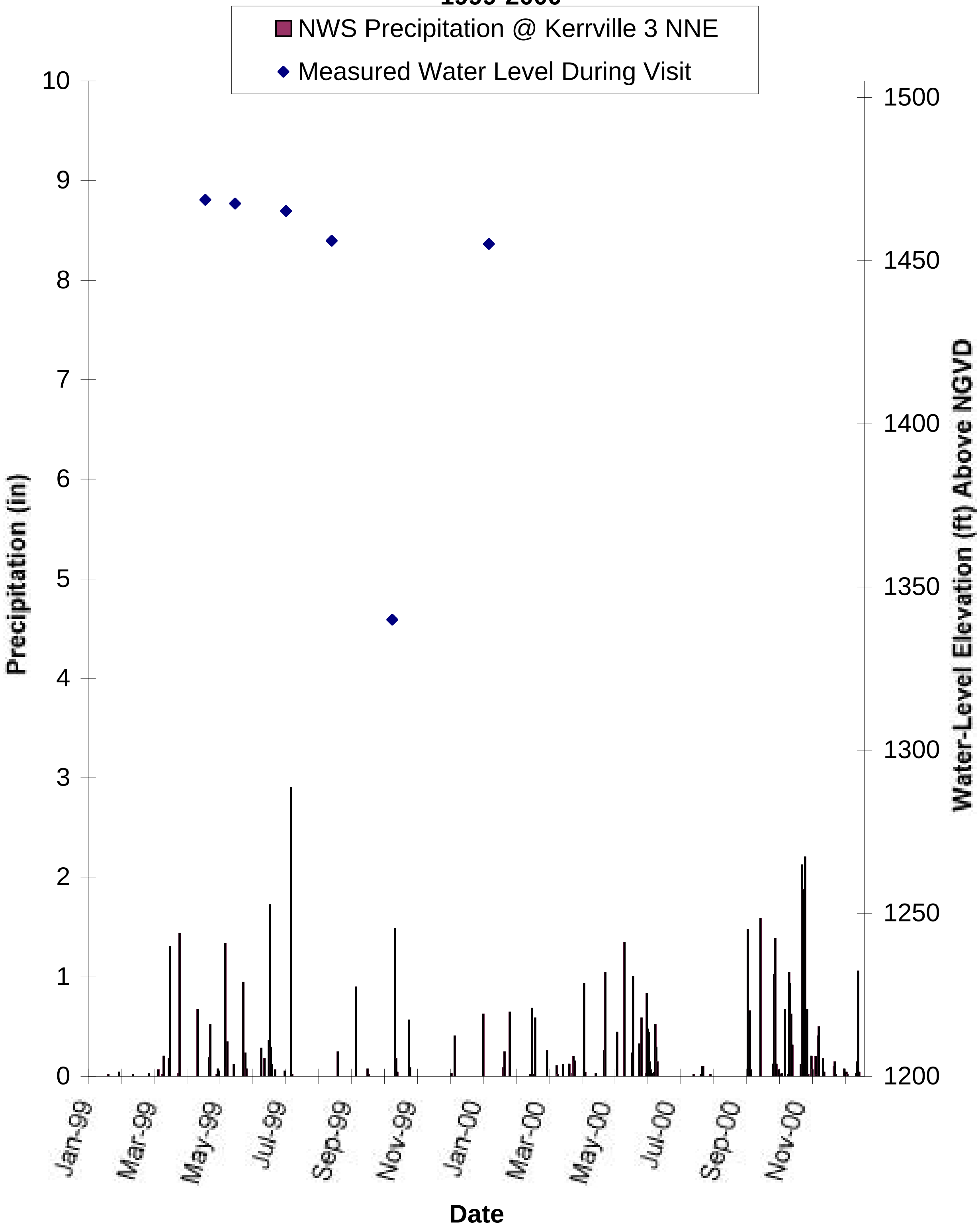


Figure 27. Kerr County, TX
Well ID # 68-09-501 (site 24)
1999-2000